Laser Measurements & Technology

The Laboratory for Terrestrial Physics contains three organizations which are primarily measurement and instrument oriented - the Geoscience Technology Office, the Space Geodesy and Sensor Calibration Office, and the Laser Remote Sensing Branch.

The **Geoscience Technology Office** develops advanced mission concepts and the associated components and instrumentation required to carry them out. It is composed of personnel with broad experience in the analysis and development of both active and passive optical sensors and often supports the activities of the other two technical organizations within the Laboratory. Under priorities established by the Chief of the Laboratory and his Associates, the GTO performs advanced mission analyses and simulations, evaluates and selects from among technical options for making a new or improved scientific measurement, identifies the technological "tall poles", develops the enabling hardware and software, performs appropriate field (ground, air, or space) experiments to demonstrate the technology, and works with other Laboratory entities to infuse these new technologies into future ground networks or spaceborne science missions.

The **Space Geodesy Networks & Sensor Calibration Office** manages and operates the NASA Satellite Laser Ranging (SLR) and Very Long Baseline Interferometry (VLBI) Networks in support of global space geodesy and Solid Earth geodynamics. The Office also provides the Earth science research community with a broad range of expertise in calibration and characterization of optical remote sensing instrumentation from the ultraviolet to the near infrared and through all phases of spaceflight.

The **Laser Remote Sensing Branch's** mission is to develop laser remote sensing techniques and instruments for scientific measurements of the Earth and planets. Activities include developing and demonstrating new measurement techniques, conducting experiments, and developing ground-based, airborne, and spaceborne laser sensors (lidars). The Branch's work is usually multidisciplinary, and involves theoretical and experimental activities in applied physics, technology development and instrument engineering. Some activities include planning and participating in scientific field campaigns, analyzing the laser measurement and laser sensor performance, acquiring and interpreting lidar data, and developing lasers, optics, and detector components. The Branch's work often involves collaborations with application scientists within Goddard, at universities or other government laboratories, and with researchers and engineers who specialize in lasers and electro-optics.

Geoscience Technology Office

To enable new Earth science and planetary missions in the future and to make the most efficient use of resources, the Laboratory for Terrestrial Physics (LTP) develops advanced mission concepts and their associated technologies. The Geoscience Technology Office is currently investigating several new photon-counting laser ranging instruments to meet the needs of a variety of science applications. These include the automated SLR2000 Satellite Laser Ranging (SLR) station, a Breadboard Interplanetary Laser Transponder, and Multikilohertz Microlaser Altimeter ("Microaltimeter"). The aforementioned instruments have some common features including:

- Multi-kilohertz laser fire and sampling rates (2 to 10 kHz)
- Single photon detection in the visible wavelength regime at 532 nm
- A 24 hour operational capability, i.e. day/night operations
- Mean signal strengths less than one photoelectron per laser fire

- Signal-to-Noise Ratios (SNR) much less than unity during daylight operations

- Sub-nanosecond pulse widths for high ranging precision generated by a compact, passively Q-switched microlaser measuring a few mms in length.

- Small to modest telescope apertures (14 to 40 cm)

- Low to moderate laser output powers (7 to 300 mW)

- Reliable signal extraction relies on the fact that the signal photons collected over many laser fires are "bunched together" in time ("temporally coherent") while background solar noise photons are randomly distributed.

Photon-counting, microlaser-based instruments have several advantages over conventional high SNR systems:

- They require smaller power-aperture products to perform the same number of measurements. This implies a lighter, more compact instrument with reduced power consumption and lower fabrication costs. These qualities make it especially attractive for use in spaceborne missions, both Earth orbit or interplanetary.

- They offer orders-of-magnitude increase in sampling rates and spatial resolution. In rangers and transponders, the instrument rapidly drives down random errors and reproduces the target array/source impulse response for improved accuracy in the range data. Thus, the ability to control systematic and/or calibration errors is enhanced in photon-counting mode. In altimeters using detector arrays or segmented anode photomultipliers, one can approximate "point-to-point ranging" and "quasi-3D imaging" by measuring the round-trip flight times of individual photons to achieve improved resolution in both the transverse and vertical coordinates. In addition, the smaller system apertures and kilohertz repetition rates greatly expand the options for scanning the beam to achieve improved along-track and/or cross-track visualization and resolution.

- They result in lower single pulse radiation fluxes both on the ground and within the instrument. This increases system reliability by reducing the risk of internal optical damage and improves the margin of safety for ground-based observers.

- System reliability and ranging accuracy is improved through the use of small, monolithic, passively Q-switched, microlaser transmitters which are extremely simple in their construction and operation, require no failure-prone high speed or pulsing electronics, and never go out of alignment.

During this reporting period, the Geoscience Technology Office provided algorithm and software leadership for the Mars Orbiter Laser Altimeter (MOLA), the Geoscience Laser Altimeter System (GLAS), and the Mercury Messenger Laser Altimeter (MLA) and has supported inhouse technical reviews of the GLAS and MLA transmitters. With the retirement of LTP Associate Chief, Jack Bufton, the Geoscience Technology Office has taken over the technical leadership responsibilities for the MultiBeam Laser Altimeter (MBLA) transmitter development for the Vegetation Canopy Lidar (VCL) and the next generation of the Shuttle Laser Altimeter (SLA-03), which will provide a spaceborne demonstration of the photon-counting approach to laser altimetry. Several R&D projects related to improved solid state laser transmitters to support altimetric and atmospheric remote sensing activities have also been funded by the Earth Science Technology Office (ESTO), the Goddard Director's Discretionary Fund (DDF), and NASA's Small Business Innovative Research (SBIR) Program.

SLR2000 Autonomous Satellite Laser Ranging Station

Unlike the current manned Satellite Laser Ranging (SLR) systems operated by the Space Geodesy Networks & Sensor Calibration Branch, NASA's next generation SLR2000 system is designed to be fully autonomous and eye-safe and to perform millimeter precision ranging to the full constellation of satellites at altitudes up to 20,000 km above sea level. All of the satellites are equipped with passive retroreflectors, which reflect a small portion of the light back to the station. The range to the satellite is obtained by measuring the roundtrip time-of-flight of the laser photons to a few trillionths of a second and using models to correct for atmospheric refraction. Like its manned predecessors, SLR2000 has numerous scientific applications including maintenance of the terrestrial reference frame, precise orbit determination, geophysics, gravity, fundamental physics, and global time transfer. Although 532 nm is not an eye-safe wavelength, SLR2000 achieves eye safety by reducing the transmitted single pulse energy by almost three orders of magnitude [from 100 mJ for the manned NASA Mobile Laser Ranging Stations (MOBLAS) system to 135 µJ] and by utilizing the full 40 cm aperture of the common transmit/receive telescope in transmitting the laser energy. The MOBLAS system also has a larger receive aperture (76 cm vs 40 cm), resulting in an overall single shot signal advantage for MOBLAS of 2667 to 1 relative to SLR2000.

To compensate for this huge discrepancy in the number of received photons per laser fire, the SLR2000 system is operated at a much higher 2 kHz rate compared to 5 Hz for MOBLAS. Thus, the time-averaged transmitted laser power for SLR2000 of 270 mW (135 µJ at 2 kHz) is within a factor of 2 of the 500 mW transmitted by the conventional high power MOBLAS station (100 mJ at 5 Hz). Furthermore, the laser beam divergence is narrowed from roughly 30 arcseconds to 10 arcseconds so that a significantly greater fraction of the energy is concentrated on the target. The resulting factor of 9 beam divergence advantage, multiplied by the factor of 400 repetition rate advantage, actually gives SLR2000 a slight edge (3600/2667 = 1.35) over MOBLAS with respect to the mean number of photons received per unit time.

By the end of CY01, all of the SLR2000 subsystems were completed and tested. The primary achievement this year was the successful delivery of an arcsecond precision tracking mount, shown in Figure 1. The prototype SLR2000 system is currently being integrated and readied for field testing at the Goddard Geophysical and Astrophysical Observatory (GGAO). Field tests are scheduled to be completed by the end of CY02.

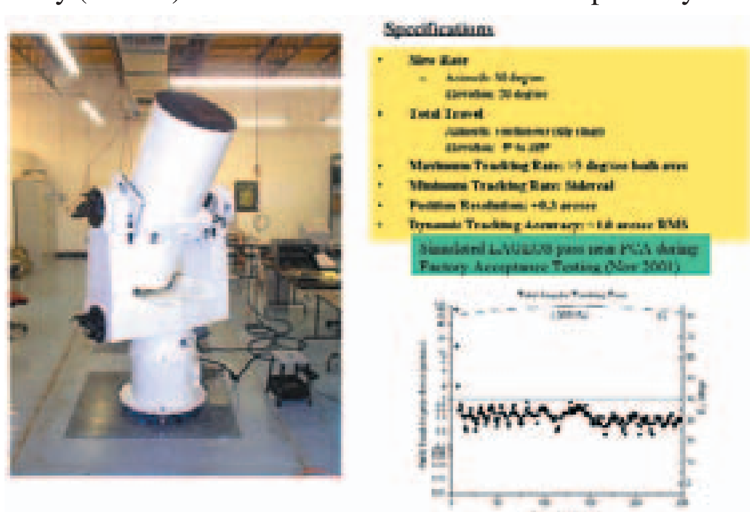

Figure 1: Photo of the prototype SLR2000 Tracking Mount, list of primary specifications, and the experimental data from a simulated LAGEOS satellite track, which was taken during Factory Acceptance Testing and shows sub-arcsecond tracking precision.

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Interplanetary Laser Transponders

The theoretical ability of SLR2000 to use "temporal coherence" to extract a weak satellite ranging signal as small as 0.0001 photoelectron per fire from the much stronger solar background led us to consider the feasibility of interplanetary laser transponders. Over interplanetary distances, the signal returns from passive reflectors are too weak and the time delays between the transmission and detection of a pulse are too long for a practical link. Thus, a laser is placed at both ends of the link.

In an asynchronous transponder, the two terminals independently fire pulses at each other. Figure 2a presents a timing diagram for an SLR2000 Earth station exchanging pulses (at the nominal SLR2000 laser fire rate of 2 kHz) with the breadboard interplanetary laser transponder in Figure 2b. The latter was built in FY98 under the Goddard Director's Discretionary Fund and sized for an Earth-Mars link with SLR2000. The SLR2000 Earth terminal records the times of departure of its own transmitted pulses and the intermittent times of arrival of pulses from Mars and vice versa. The departure and arrival times measured at each terminal are then communicated to, and properly paired at, a common processor on Earth, which then calculates the range and clock offset between the two terminals.

Such transponders would permit decimeter accuracy or better ranging and sub-nanosecond time transfer between Earth and a spacecraft operating anywhere within the inner Solar System, e.g. out to the asteroid belt beyond Mars. Science applications would include precise planetary or asteroid ephemeredes and librations, solar and solar system physics, and enhanced General Relativity experiments carried out on an interplanetary scale.

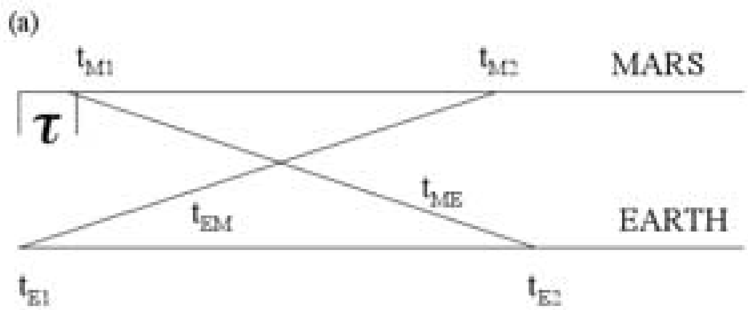

Figure 2a. Timing diagram for transponder link between Earth and Mars

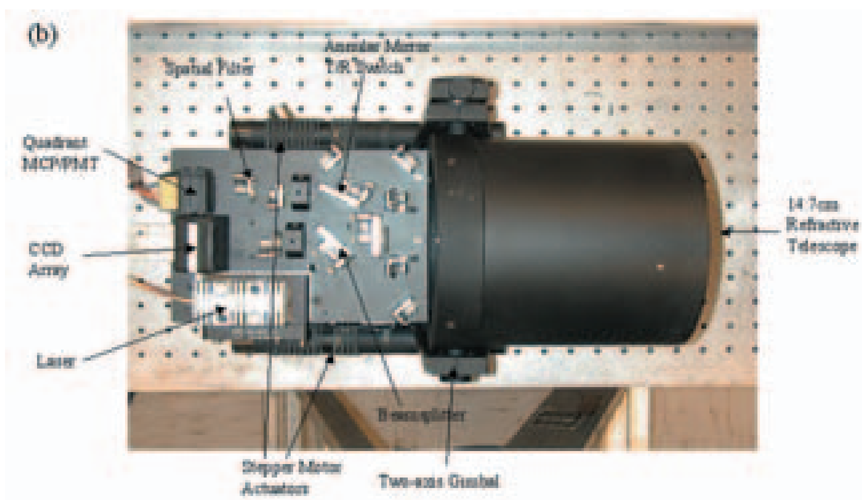

Figure 2b. Photo of the DDF Interplanetary Laser Transponder Breadboard

After a long hiatus due to insufficient manpower, we returned this year to setting up a laboratory simulation of the Earth-Mars link. In August 2001, two students from the University of Deggendorf in Germany, Christian Wimmer and Elmar Pitschke, were brought into our laboratory via the GEST Program and have completed the first of three simulation phases. In this phase, the incoming and outgoing pulses were simulated electronically, allowing for large range rates of up to 65 km/sec due to planetary motion. Software was developed to read the data from two new timers, to correct the raw data for the nominal relative motion between terminals, and to create a range histogram showing the buildup of signal in a single bin. The second phase will attempt to provide a more realistic Signal-to-Noise ratio through the use of two ultrashort pulse Light Emitting Diodes (LED's) to simulate the single photon returns, a VARIAC-controlled light bulb to simulate the noise background, and fast optical detectors to generate the pulse inputs to the timers.

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Airborne Multikilohertz Microlaser Altimeter

During 2001, we completed the development and preliminary flight testing of a photon counting airborne microlaser altimeter, or "microaltimeter". The instrument, developed under NASA's Instrument Incubator Program (IIP), operates at multi-kHz rates from aircraft cruise altitudes with a single pulse energy of a few μJ and a 14 cm diameter off-axis telescope, which is spatially shared by the transmitter and receiver. The system also uses multi-anode metal dynode chain photomultipliers in order to segment the ground image into as many as 16 elements (4x4 "pixels"). Each of the anodes is input to an independent timing channel so that the altimeter can be operated in a 3D imaging mode. For increased portability between aircraft, the instrument is packaged to fit into a standard Lyca camera mount, which is widely used in airborne mean signal strength exceed 3 pe per laser fire.

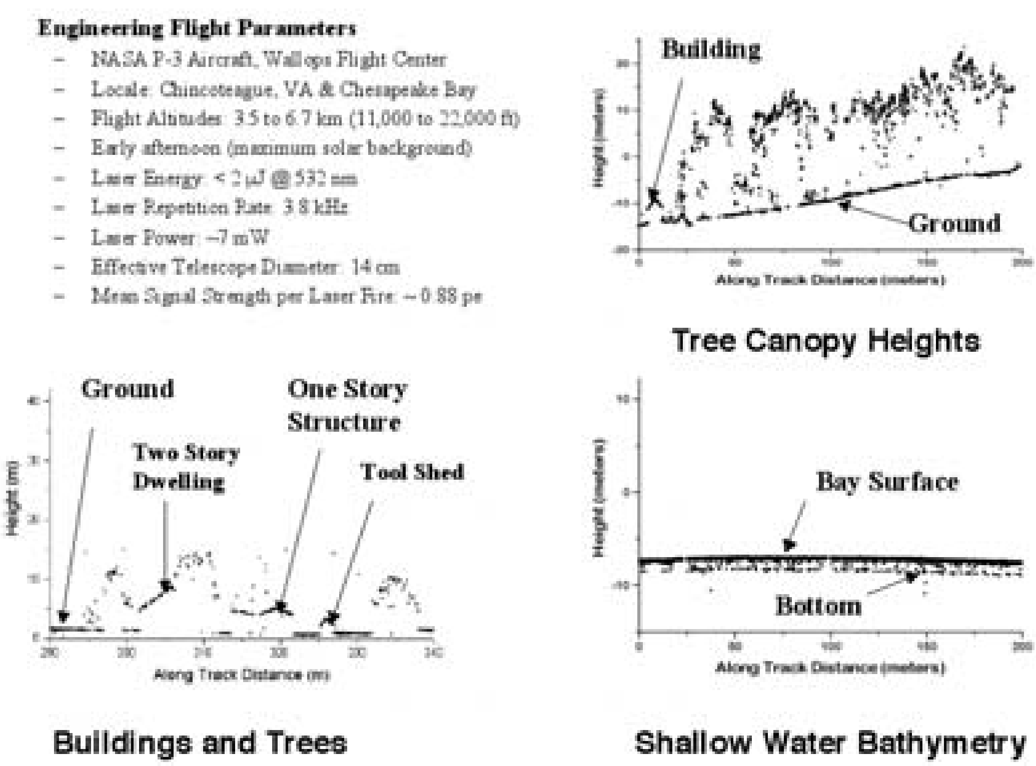

Figure 3.

Figure 3 provides a summary of the instrument parameters for the first engineering flight and some sample profiling data, taken between noon and 2 pm at altitudes between 3.3 and 6.7 km. At the highest altitude of 6.7 km (22,000 ft), the mean signal strength per laser fire was computed to be less than 0.88 photoelectron (pe) per laser fire; at no altitude did the calculated mean signal strength exceed 3 pe per laser fire. The system successfully generated high resolution profiles of buildings, tree canopies and underlying terrain, and even performed shallow water bathymetry over the Chesapeake Bay. Each of the figures shows 2 second samples or less of altimetry data, and this early engineering data is uncorrected for aircraft motion or attitude. Later flights used a conical scanner to generate 3D contour plots of the region.

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Vegetation Canopy Lidar

The Vegetation Canopy Lidar (VCL) laser transmitter development overcame numerous hurdles in 2001 to finally arrive at the point of assembling the first laser for flight qualifications. The three VCL flight lasers are to be mounted around the perimeter of the 0.9 m diameter parabolic receiving mirror of the Multi Beam Laser Altimeter (MBLA). At the beginning of the mission, each laser is to produce ~ 15 mJ of energy per pulse at a repetition rate of 242 Hz with < 60 μrad divergence over an operational temperature range of over 10ºC. VCL will measure the Earth's vegetation volume over two years and will greatly reduce the current unknowns within the planet's carbon cycle calculations.

Due to losses in optics required for beam shaping and expansion, the laser must produce 17 mJ per pulse in order to meet the 15 mJ output specification. The laser operates in the lowest order spatial mode with a near-Gaussian output spatial profile. The laser produces the specified energy over a temperature range of 10ºC - 35ºC, with pulsewidths of ~ 10 ns. The VCL transmitter has achieved >14% optical efficiency. When coupled with pump electronics and passive radiative cooling, the true "wall-plug" efficiency is > 6%. To our knowledge, the VCL transmitter is the most efficient oscillator-only Nd:YAG design of its kind ever developed. This efficiency is 67% greater than the Mars Orbiting Laser Altimeter (MOLA), which recently finished mapping Mars. Considering that MOLA was a highly multimode laser, the VCL laser efficiency represents the state of the art for diode pumped lasers.

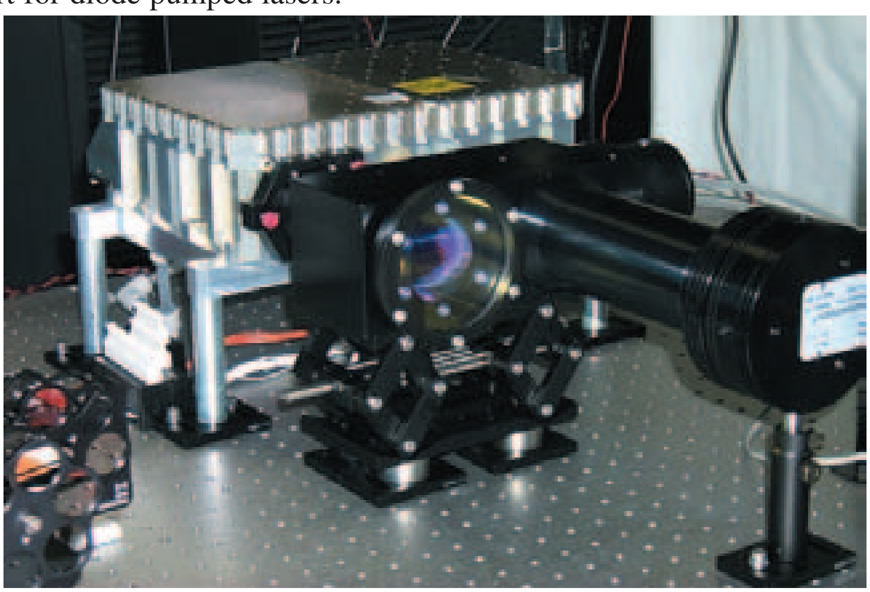

Figure 4. VCL Transmitter with test fixture.

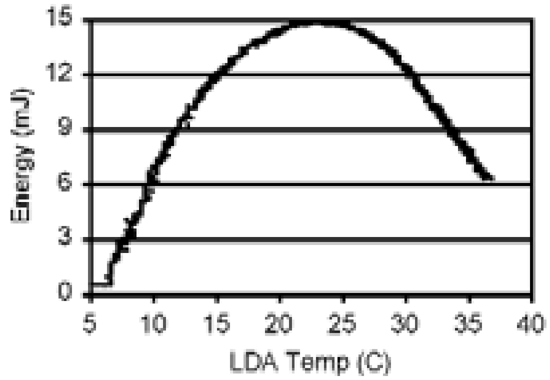

Figure 5. Performance vs Temperature

The government took over the hardware design and build effort from the prime laser contractor in late 2000 after he was unable to meet system specifications. A series of problems, both in design and material, were discovered as we proceeded to install and test components. Most of the components and procedures had to be reworked, including the thermal conductive mounting technique for the laser slab, the slab bonding procedure, the laser head clamping assembly, all of the optical mounts, the output telescope, etc. In addition, many materials had to be changed or altered to meet cleanliness and performance specifications. Due to poor initial material selection, we were forced to silver coat the optical bench screws for lubrication and contamination control and select optical mount materials that matched the thermal expansion coefficients of the optics. The laser drive and timing electronics had to be modified to take advantage of the improved cavity efficiency; failure to do so would have resulted in a shorter-lived system with excessive output power. Most importantly, a thorough acceptance, inspection, and testing process was developed, where none had previously existed, for procuring flight-ready optics. Overall, about half of the optics received from vendors were either returned for reorder or tagged as an "emergency backup" item due to poor quality or insufficient optical damage threshold. All of the aforementioned issues listed above, as well as many others, have been resolved and the appropriate procedures and documentation have been updated.

Our final remaining issue resides with the most critical component: the Nd:YAG laser slab. We have discovered what we believe is a coating process problem at the manufacturer. They have been very responsive and are working closely with us in improving the slab's coating quality. A microspotting or pitting, which we believe is contamination-induced, evolves on one of the slab's 2 coated surfaces over 10's of millions of shots. These spots eventually occlude enough of the intracavity beam area and the laser output power degrades to unacceptable levels. Due to VCL's high efficiency specification, these custom coatings are necessary and standard industry techniques simply would not work. A solution is at hand and, as of this writing, three new slabs are being coated using a cleaner and more robust process. By the end of February 2002, the first protoflight laser will begin environmental testing. In parallel, the first of three flight lasers will begin preassembly processing.

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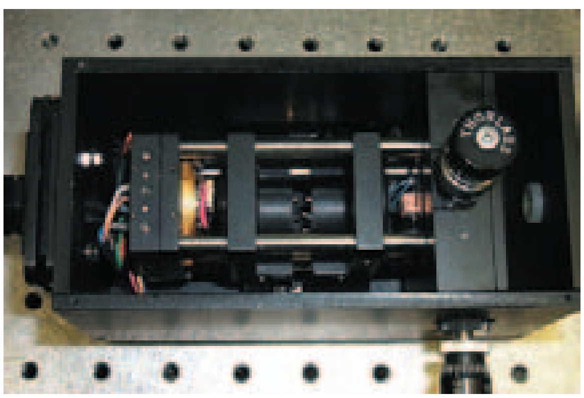
Laser Diode-Based Single Longitudinal Mode (SLM) Seeder for Nd:YAG Lasers

A 2nd year DDF project was completed in 2001 with the successful seeded operation (Figure 7) of the VCL breadboard laser with a diode laser based seeder (Figure 6). This seeder unit, shown at left, was developed in conjunction with AdvR Inc, a small company in Bozeman, MT. This item does not exist in the marketplace, and, if properly developed, can quickly evolve into a significant product in the OEM and scientific laser industry. Single Longitudinal Mode (SLM) operation of a high power laser greatly reduces the risk of optical damage and increases is operational lifetime. Most importantly, a stable SLM source is essential for most atmospheric lidar techniques. High power, SLM solid state lasers are expensive since they require several intracavity frequency control optics, active cavity alignment feedback, as well as an external, self-contained miniature diode pumped seed lasers. External seed lasers are expensive, sensitive to the environment, have a high part count, and can be unreliable. We have produced an externally tuned diode laser device by etching a Bragg diffraction grating into a KTP crystal. By gold plating certain regions of this crystal, we can drive the grating spacing with voltage. Thus, no moving parts are needed and an electro-optic frequency tuning element is created. Further funding has been approved by the Earth Science Technology Office (ESTO) and work will begin in 2002 for the development of a self contained, miniature packaged device, capable of flight qualification.



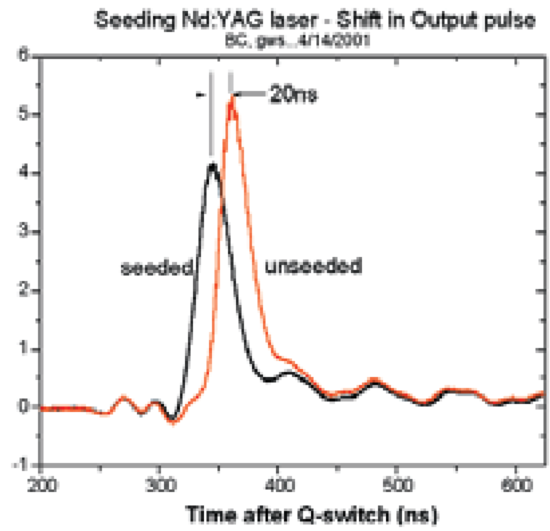


Figure 6. (left) Figure 7. (right)

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One Micron Testbed

We were awarded Code Y funds for Goddard's "One Micron Testbed" project: a 3 year effort pursuing the development and refinement of advanced diode pumped solid state laser technology for future laser-based remote sensing instruments. This effort sprung from the difficulties that GSFC, and the laser industry as a whole, have experienced in delivering reliable laser transmitters for space-based remote sensing. We are tasked to build a brassboard transmitter with several new, but tested, technologies with record efficiencies, optimum beam quality, high reliability, and repeatability. Included in this effort are parallel funded projects in optics bonding, optics processing, optical coating damage threshold characterization, cleanliness and component processing. The final laser will be constructed in concert with other Goddard groups with the end goal of reduced risk and increased laser lifetime. Many of these techniques have evolved from lessons learned on VCL, GLAS, MOLA and several past in-house laser designs from aircraft altimeter projects. The "one micron testbed" is an effort to apply all these lessons to a single laser.

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Passively Q-Switched Yb:YAG laser transmitter

A phase II Small Business Innovative Research (SBIR) program with MIT-Lincoln Labs was completed in 2001 with a delivered laser oscillator based on a relatively new gain material with promising properties. While this system does not achieve the theoretical improvement in system efficiency over a similar Nd:YAG-based system, important technology was developed in packaging such a crystal for use outside the laboratory. In order to achieve higher efficiencies, the new Yb:YAG gain material must be housed in a vacuum environment, and cooled to subzero temperatures. The vacuum is needed to remove any risk of condensation on the crystal or surrounding optics. The new laser head consists of a miniature windowed vacuum chamber housing a Yb:YAG laser crystal mounted to a "cold-finger". The cold finger is part of a miniature closed cycle sterling engine, an efficient method for achieving sub-zero temperatures. This material warrants further study for eventual use in space-based laser instruments. In the vacuum of space, the power required to drive a vacuum chamber would obviously be eliminated from the equation, and the Yb:YAG's theoretical efficiencies may be achieved.

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High Repetition Rate Q-switched Nd:YLF Laser for Terrain Mapping

A phase II SBIR with Q-Peak Inc. was completed in 2001 with the delivery of a diode pumped Nd:YLF laser. This laser operates in the "difficult" 1 kHz pulse repetition rate regime and still produces 6 mJ pulses. This rep rate is "difficult" because of the need for careful heat removal, and thermal lensing control and a high diode array duty cycle. This laser, unlike the previously discussed Yb:YAG system from MIT, can be readied for aircraft-based use with some minor opto-mechanical improvements in the laser bench and mounts. It will be retrofitted into the LVIS (Laser Vegetation Imaging Sensor) altimetry system. LVIS was the airborne test platform for the original VCL concept and is slated for numerous aircraft under-flights as part of the VCL mission support.

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Space Geodesy and Sensor Calibration Office

The Space Geodesy Networks and Sensor Calibration office provides management and technical direction for two NASA Space Geodetic Networks, the NASA Satellite Laser Ranging (SLR) Network and the Very Long Baseline Interferometry (VLBI) network for the laboratory's capability for calibration and characterization of remote sensing science instrumentation. This includes management of nine NASA SLR stations, four VLBI stations, and the coordination and technical leadership of over seventy cooperating permanent global stations. The scope of the work includes all phases from science experiment planning and operations to engineering and science data processing.

The office is also involved in the International Laser Ranging Service (ILRS), which provides global satellite and lunar laser ranging data and their related products to support geodetic and geophysical research activities as well as International Earth Rotation Service (IERS) products important to the maintenance of an accurate International Terrestrial Reference Frame (ITRF). The service develops the necessary global standards/specifications and encourages international adherence to its conventions.

The Space Geodesy Networks and Sensor Calibration office also provides the Earth science research community with a broad range of expertise in calibration and characterization of remote sensing instrumentation from the ultraviolet to the near infrared and assists in extending the state of the art in optical radiometry. The office operates specialized calibration laboratories for sensors in the visible and near infrared bands. It also develops enhanced techniques for instrument calibration and characterization through all phases of spaceflight. The office is responsible for developing and tracking the EOS MODIS Level 1B calibration algorithm.

International Laser Ranging Service (ILRS)

The ILRS was established in 1998 and is an Official Service of the International Association for Geodesy (IAG). The ILRS collects, merges, analyzes, archives and distributes Satellite Laser Ranging (SLR) and Lunar Laser Ranging (LLR) observation data sets of sufficient accuracy to satisfy the objectives of a wide range of scientific, engineering, and operational applications and experimentation. The basic observable is the precise time-of-flight of an ultrashort laser pulse to and from a satellite, corrected for atmospheric delays. These data sets are used by the ILRS to generate a number of fundamental data products, including: centimeter accuracy satellite ephemerides, Earth orientation parameters, three-dimensional coordinates and velocities of the ILRS tracking stations, time-varying geocenter coordinates, static and time-varying coefficients of the Earth's gravity field, fundamental physical constants, lunar ephemerides and librations, and lunar orientation parameters. The ILRS consists of several operational elements: tracking stations, operational centers, analysis centers, and data centers.

ILRS Tracking Stations range to a constellation of over 20 artificial satellites and the Moon with state-of-the-art laser ranging systems and transmit their data on a rapid basis (at least daily) to an Operations or Data Center. Each Tracking Station is typically associated with one of the three regional subnetworks (National Aeronautics and Space Administration (NASA), EUROpean LASer Network (EUROLAS), or the Western Pacific Laser Tracking Network (WPLTN). The global ILRS Network is shown in Figure 8.

Figure 8. Current ILRS Network

ILRS Operations Centers collect and merge the data from the tracking sites, provide initial quality checks, reformat and compress the data if necessary, maintain a local archive of the tracking data, and relay the data to a Data Center.

The two Global Data Centers are located at GSFC and at the European Data Center in Bonn, Germany, and are the primary interfaces between the Analysis Centers and the science users. They receive and archive ranging data and supporting information from the Operations and Regional Data Centers, and provide this data on-line to the Analysis Centers. They also receive and archive ILRS scientific data products from the Analysis Centers and provide these products on-line to users. Regional Data Centers reduce traffic on electronic networks and provide a local data archive.

Analysis Centers receive and process tracking data to produce ILRS data products. They are committed to produce the products on a routine basis for delivery to the Global Data Centers and to the International Earth Rotation Service (IERS) according to designated standards. Full Analysis Centers routinely process the global LAGEOS-1 and LAGEOS-2 data and provide Earth orientation parameters on a weekly or sub-weekly basis. They also produce other products such as station coordinates and velocities and geocenter coordinates on a schedule consistent with IERS requirements and provide a second level of data quality assurance in the network. Associate Analysis Centers produce specialized products, such as time-varying gravity field measurements, fundamental constants, satellite predictions, precision orbits for special-purpose satellites, regional geodetic measurements, and data products of a mission-specific nature. Associate Analysis Centers are also encouraged to perform quality control functions through the direct comparison of Analysis Center products and the creation of "combined" solutions using data from other space geodetic techniques, such as Very Long Baseline Interferometry (VLBI) and the Global Positioning System (GPS). Lunar Analysis Centers produce Lunar Laser Ranging (LLR) products such as lunar ephemeris, lunar libration, and Earth rotation (UT0 - UT1). In studies of relativity, LLR is used for the verification of the equivalence principle, estimation of geodetic precession, and examination of the relative change in G.

Central Bureau

The ILRS Central Bureau (CB) is located at the Goddard Space Flight Center and is responsible for the daily coordination and management of ILRS activities. The CB facilitates communications and information transfer and promotes compliance with ILRS network standards. The CB monitors network operations and quality assurance of the data, maintains all ILRS documentation and databases, and organizes meetings and workshops. In order to strengthen the ILRS interface with the scientific community, a Science Coordinator and an Analysis Specialist within the CB take a proactive role to enhance dialogue, to promote SLR goals and capabilities, and to educate and advise the ILRS entities on current and future science requirements related to SLR. The Science Coordinator leads efforts to ensure that ILRS data products meet the needs of the scientific community and there is easy online access to all published material (via Abstracts) relevant to SLR science and technology objectives.

The CB has been actively providing new conveniences (such as targeted email exploders) and adding to the technical and scientific database. The information available via the ILRS Web Site has grown enormously since its inception, and many new links to related organizations and sites have been established. The site provides details and photographic material on the ILRS, the satellites and campaigns, individual SLR station characteristics, a scientific and technical bibliography on SLR and its applications, current activities of the Governing Board Working Groups and Central Bureau, meeting minutes and reports (including annual reports), tracking plans, etc. In the future, much more material will be made available online along with an enhanced search capability to quickly isolate specific material of interest. During the past year, Dr. Michael Pearlman of SAO assumed the role of CB Director following the retirement of John Bosworth, and Ms. Carey Noll (Code 922) assumed Dr. Pearlman's previous role of ILRS Secretary.

The Central Bureau maintains a comprehensive web site as the primary vehicle for the distribution of information within the ILRS community. The site, which can be accessed at http://ilrs.gsfc.nasa.gov, includes the following major topic titles: About the ILRS, Current Events, Working Groups, Satellite Missions, Network Stations, Data Products, Science/Analysis, Engineering/Technology, Reports, Frequently Asked Questions (FAQs), and Links. Mirrored sites are also available at the Communications Research Laboratory (CRL) in Tokyo and the European Data Center (EDC) in Munich. The site also includes SLR related bibliographies, Earth science links, historical information, colocation histories, and mail exploders. An on-line brochure provides charts for SLR presentations. A hard copy library of early documentation has been assembled and is listed in the on-line bibliography. A new ILRS Reference Card was recently developed to provide easy online access to much of this material and to targeted email exploders.

Governing Board and Working Groups

The Governing Board (GB) is responsible for the general direction of the service. It defines official ILRS policy and products, determines satellite tracking priorities, develops standards and procedures, and interacts with other services and organizations. There are 16 members of the GB - three are ex-officio, seven are appointed, and six are elected by their peer groups (see Table 1).

Table 1. Current ILRS Governing Board

Hermann Drewes	Ex-Officio, CSTG President	Germany
Michael Pearlman	Ex-Officio, Director ILRS Central Bureau	USA
Carey Noll	Ex-Officio, Secretary, ILRS Central Bureau	USA
Werner Gurtner	Appointed, EUROLAS , Networks & Eng. WG Coordinator	Switzerland
Wolfgang Schlueter	Appointed, EUROLAS, Networks & Eng. WG Deputy Coord.	Germany
David Carter	Appointed, NASA	USA
John Degnan	Appointed, NASA, Governing Board Chairperson	USA
Yang FuMin	Appointed, WPLTN	PRC
Hiroo Kunimori	Appointed, WPLTN, Missions WG Coordinator	Japan
Bob Schutz	Appointed, IERS Representative to ILRS	USA
Graham Appleby	Elected, Analysis Rep.	UK
Ron Noomen	Elected, Analysis Rep. , Analysis WG Coordinator	Netherlands
Wolfgang Seemueller	Elected, Data Centers Rep. , Data Formats & Procedures WG Deputy Coordinator	Germany
Peter Shelus	Elected, Lunar Rep., Analysis WG Deputy Coordinator	USA
Georg Kirchner	Elected, At-Large, Missions WG Deputy Coordinator	Austria
John Luck	Elected, At-Large, Data Formats & Procedures WG Coordinator	Australia

Within the GB, permanent (Standing) or temporary (Ad-Hoc) Working Groups (WG's) carry out policy formulation for the ILRS. At its creation, the ILRS established four Standing WG's: (1) Missions, (2) Data Formats and Procedures, (3) Networks and Engineering, and (4) Analysis. In 1999, an Ad-Hoc Signal Processing WG was organized to provide improved satellite range correction models to the analysts. The Working Groups are intended to provide the expertise necessary to make technical decisions, to plan programmatic courses of action, and are responsible for reviewing and approving the content of technical and scientific databases maintained by the Central Bureau. All GB members serve on at least one of the four Standing Working Groups, led by a Coordinator and Deputy Coordinator. Table 1 lists the current GB membership, their nationality, and special function (if any) on the GB.

The Missions WG has formalized and standardized the mission documentation required to obtain ILRS approval for new missions and campaigns. They continue to work with new missions and campaign sponsors to develop and finalize tracking plans and to establish recommended tracking priorities. The Data Formats and Procedures WG has been tightening up existing formats and procedures, rectifying anomalies, providing standardized documentation through the web site, and setting up study subgroups and teams to deal with more complicated or interdisciplinary issues. The Networks and Engineering WG has (1) developed the new ILRS Site and System Information

Form which is being distributed to the stations to keep the engineering database current, (2) provided a new online satellite-link analysis capability for system design and performance evaluation, and (3) initiated the development of the ILRS technology database. The Analysis WG has been working with the ILRS Analysis Centers to develop a unified set of analysis products presented in the internationally accepted SINEX format. Three associated pilot programs are underway to assess differences among analysis products from the different centers. The Signal Processing Ad-Hoc WG is working on improved center-of-mass corrections and signal processing techniques for the various satellites tracked by SLR.

The ILRS is currently tracking about two dozen targets, including passive geodetic (geodynamics) satellites, Earth remote sensing satellites, navigation satellites, engineering missions, and lunar reflectors (see Table 2). The Governing Board assigns tracking priorities in an attempt to maximize data yield on the full satellite complex while at the same time placing greatest emphasis on the most immediate data needs. Once tracking support is approved by the Governing Board, the Central Bureau works with the new missions to develop a Mission Support Plan detailing the level of tracking, the schedule, the points of contact, and the channels of communication. New missions normally receive very high priority during the acquisition and checkout phases and are then placed at a routine priority based on the satellite category and orbital parameters. After launch, New Mission Reports with network tracking statistics and operational comments are issued weekly. The Central Bureau monitors progress to determine if adequate support is being provided. New mission sponsors (users) are requested to report at the ILRS Plenary meetings on the status of ongoing campaigns, including the responsiveness of the ILRS to their needs and on progress towards achieving the desired science or engineering results.

Table 2. Current ILRS Tracking Priorities (excluding four lunar targets)

Priority	Mission	Sponsor	Altitude (km)	Inclination (degrees)	Comments
1	CHAMP	GFZ, Germany	429-474	87.27	Gravity research
2	Starshine 3	US Cooperative	470	67	Drag research / no other tracking technique available
3	GFO1	US Navy	790	108.0	Altimeter POD/calibration / no other tracking technique
4	ERS2	ESA	800	98.6	Altimeter calibration /PRARE backup
5	Jason	NASA/CNES	1,350	66.0	Altimeter / DORIS and GPS backup
6	TOPEX/Poseidon	NASA/CNES	1,350	66.0	Altimeter calibration / DORIS and GPS backup
7	Stella	CNES	815	98.6	Geodetic / / no other tracking technique available
8	Starlette	CNES	815-1,100	49.8	Geodetic / / no other tracking technique available
9	Meteor-3M	NASA/IPIE, Russia	1020	99.64	Retroreflector research / Tracking by 2 NASA sites only
10	REFLECTOR	IPIE, Russia	1,020	99.6	POD research for space debris detection
11	BeaconC	NASA	950-1300	41	Gravity Research / upgraded to ongoing mission (Jan 2002)
12	Ajisai	NASDA	1,485	50	Geodetic / / no other tracking technique available
13	LAGEOS2	NASA/ASI, Italy	5625	52.6	Geodetic / / no other tracking technique available
14	LAGEOS1	NASA	5850	109.8	Geodetic / / no other tracking technique available
15	Etalon1	Russia	19,100	65.3	Geodetic / / no other tracking technique available
16	Etalon2	Russia	19,100	65.2	Geodetic / / no other tracking technique available
17	GLONASS80	Russia	19,100	65	Positioning POD enhancement / replaced G70 as of 10/20/99
18	GLONASS78	Russia	19,100	65	Positioning POD enhancement / replaced G72 as of 6/29/00
19	GLONASS84	Russia	19,100	65	Positioning POD enhancement / replaced G79as of 2/22/01
20	GPS35	US DoD	20,100	54.2	Positioning POD enhancement
21	GPS36	US DoD	20,100	55.0	Positioning POD enhancement

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NASA Satellite Laser Ranging (SLR) Network

Satellite Laser Ranging (SLR) is a fundamental measurement technique used by the NASA Space Geodesy Program to support both national and international programs in Earth dynamics, ocean and ice surface altimetry, navigation and positioning, and technology development. The SLR technique was first developed by NASA's GSFC in the early 1960's as a tool for precision orbit determination and validation of radio tracking techniques. Since 1969, NASA has built eight trailer-based Mobile Laser Ranging Stations (MOBLAS) that could be relocated to accommodate user needs. For the past fifteen years, five of the systems have remained in operation as fixed sites. The five remaining systems were built with a flexible configuration to adapt to new technologies and improvements to increase ranging capability.

During the 1980's, NASA developed four highly compact Transportable Laser Ranging Systems (TLRS). The TLRS systems were developed in response to the need of the geophysics community to obtain SLR data at remote sites, and to support programs such as the NASA Crustal Dynamics Project, Seasat, and the Working Group of European Geoscientists for the Establishment of Networks for Earthquake Research (WEGENER) Project. The University of Texas developed the first proof of concept system, TLRS-1, in 1980.

NASA also supported the development and operation of two Observatory SLR systems at the University of Texas and University of Hawaii. Both are high performance systems with the University of Texas system having lunar ranging capability in addition to SLR.

In recent years, NASA has established overseas partnerships in order to lower the NASA cost of operations and improve the global distribution of SLR stations. Under these partnerships, NASA provides the SLR system, training, engineering support, and spare parts to maintain operations. The host country provides the site, local infrastructure, and operating crew. NASA has successfully partnered with the Australian Surveying & Land Information Group (AUSLIG) in Yarragadee, Australia (MOBLAS-5); the South African National Research Foundation/Hartelbeesthoek Radio Astronomical Observatory (HRAO) in Hartelbeesthoek, South Africa (MOBLAS-6); and the University of French Polynesia/CNES in Tahiti, French Polynesia (MOBLAS-8). NASA is currently discussing an additional partnership agreement with the University of La Plata and Comisión Nacional de Actividades Espaciales (CONAE) in Argentina for the operation of NASA's TLRS-4 system. The tentative site is the University's Radio Observatory outside of La Plata.

In summary, the NASA SLR Network currently consists of nine NASA-operated or partner-operated stations covering North America, the west coast of South America, the Pacific, South Africa, and Western Australia as shown in Table 3. Although the NASA SLR network represents less than 25% of the total ILRS tracking sites, it routinely provides over 40% of the total data volume as well as the most precise sub-cm accuracy ranging data. Most NASA sites operate 24 hours per day, 7 days per week, with a staff as small as four people.

Table 3. NASA SLR Network

Location	SLR System	Operating Agency
Monument Peak, California	MOBLAS-4	Mission Contractor (HTSI)
Greenbelt, Maryland	MOBLAS-7	Mission Contractor (HTSI)
Mount Haleakala, Maui, Hawaii	HOLLAS	University of Hawaii
Fort Davis, Texas	MLRS	University of Texas at Austin
Arequipa, Peru	TLRS-3	Universidad Nacional de San Agustin
Yarragadee, Australia	MOBLAS-5	Australian Surveying & Land Information Group
Hartebeesthoek, South Africa	MOBLAS-6	National Research Foundation
Tahiti, French Polynesia	MOBLAS-8	University of French Polynesia/CNES
La Plata, Argentina	TLRS-4	La Plata University/CONAE *

** Discussions underway*

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International VLBI Service

As part of NASA's efforts in developing partnerships within industry, government and the international community to share resources, to enhance capabilities, and to further scientific objectives, the GSFC VLBI group has been actively involved in beginning and participating in the International VLBI Service (IVS). The IVS is a Service of the International Association of Geodesy (IAG), International Astronomical Union (IAU), and Federation of Astronomical and Geophysical Data Analysis Services (FAGS). IVS is an international collaboration of organizations that operate or support VLBI components. The goals are: (1) to provide a service to support geodetic, geophysical and astrometric research and operational activities, (2) to promote research and development activities in all aspects of the geodetic and astrometric VLBI technique, and (3) to interact with the community of users of VLBI products and to integrate VLBI into a global Earth observing system.

IVS Coordinating Center at GSFC

The IVS Coordinating Center is based at Goddard Space Flight Center and is operated by NEOS (National Earth Orientation Service), a joint effort for VLBI by the U.S. Naval Observatory and NASA Goddard Space Flight Center. The mission of the Coordinating Center is to provide communications and information for the IVS community and the greater scientific community and to coordinate the day-to-day and long-term activities of IVS.

Goddard provides the web server for the Coordinating Center. The address is: http://ivscc.gsfc.nasa.gov

The Coordinating Center supported the following IVS activities:

● Directing Board support: coordinated two IVS Directing Board meetings, at Goddard Space Flight Center, USA (February 2001) and in at the Spanish Research Council in Barcelona, Spain (September 2001)

● Communications support: maintained the IVS web site, e-mail lists, and web-based mail archive files; Published the 2000 Annual Report in spring 2001, published the first edition of the IVS Newsletter in December 2001.

● Master schedules: Generated and maintained the master observing schedule for 2001.

● Meetings: Coordinated, with Local Committees, support for the first IVS Technical Operations Workshop (TOW), held at Haystack Observatory in March 2001; the second Analysis Workshop held in Greenbelt, MD in February 2001; and the second IVS General Meeting, held in Tsukuba, Japan in February 2002.

GSFC VLBI Analysis Center

The GSFC VLBI Analysis processes all 24-hour sessions from the Mark-4 correlators and submits EOP values derived from each session to the IVS within one working day of correlation. The group also analyzes all NEOS-Intensive experiments and submits the UT1 values within 3 working hours. The group has primary responsibility for the analysis and timely submission of databases and data products to IVS for the CORE, NEOS-A, NEOS-Intensive, SURVEY, and CONT sessions. The analysis group also processes all VLBA RDV sessions using the NRAO AIPS program and analyzes them with Solve. Additionally, GSFC periodically submits updated TRF and CRF solutions to IVS from global solutions using all available VLBI observations. GSFC uses, maintains, develops, and distributes the Calc/Solve analysis system. The group also engages in research and analysis activities aimed at improving the measurement and understanding of Earth rotation, improving VLBI analysis techniques and modeling, improving troposphere modeling, and maintaining and refining the celestial and terrestrial reference frames.

During 2001, the VLBI group processed and analyzed 174 24-hr geodetic sessions and 207 1-hr UT1 sessions and reported Earth orientation parameter estimates for each session to the International VLBI Service (IVS). The large VLBI analysis package Calc/Solve was maintained, upgraded, and distributed to the IVS community bimonthly. Analysis staff collaborated with NRAO and Caltech personnel to perform the astrometric analysis of the 10 VLBA calibrator survey experiments, and determined milli-arcsecond level positions of 1332 new calibrator sources, many of which can be used in geodetic VLBI sessions. VLBI solutions were used to study different ocean loading models. The VLBI data supports the modern GOT00 model more than the old Schwiderski model. This study also showed that ocean-loading admittance is not smooth across a tidal band, and the IERS recommendations to compute ocean loading for minor tides by interpolating across each band is not warranted.

IVS related information can be found at:

http://cddisa.gsfc.nasa.gov/ivsmap.gif (A map of the network.)

http://cddisa.gsfc.nasa.gov/ivscompmap.gif (All components of the service.)

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The NASA Geodetic VLBI Program

The capabilities of Very Long Baseline Interferometry (VLBI) have been developed and continually improved over the past 35 years, and NASA has been a major sponsor of the geodetic and spacecraft applications through programs at Goddard Space Flight Center and at the Jet Propulsion Laboratory. It is appropriate that as NASA expands its program in Earth system studies, NASA also continues to take the lead in advancing the space geodetic techniques that will contribute so significantly to Earth sciences in the coming decades.

VLBI has three important attributes: unique determination of the celestial reference frame and the orientation of the Earth in that frame, accuracy, and long-term stability. Only through these VLBI measurements can many of the properties of the Earth's interior be determined, such as: dynamical oblateness of the core-mantle boundary, magnetic properties of the inner and outer cores, and anelasticity of the mantle.

The VLBI definition of the scale of the Terrestrial Reference Frame (TRF), measurement of UT1-UTC, and the long term stability of the reference system and orientation of Earth in space are fundamental requirements for the geodetic measurements by all other techniques. The technological developments that have brought VLBI to its present level of accuracy are the result of international collaboration and support, led by the NASA team.

NASA VLBI Research and Development

Continual technology improvement is the basis of all experimental advances and will provide both better accuracy and more rapid delivery of results. For the global geodetic VLBI program the technology advances have been due to the leadership of the VLBI groups at Goddard Space Flight Center and at the MIT Haystack Observatory operating under a NASA contract. The implementation of these projects has been the product of large international collaborations involving many countries and agencies. Current technology emphasis is aimed at two initiatives. First is the recently initiated Mark 5 disk-based data acquisition system, which will benefit the science through better sensitivity while reducing costs and improving reliability. Second is the use of high bandwidth optical fiber communication for real-time VLBI, first demonstrated by the Communications Research Laboratory of Japan.

With the completion of the Mark 4 correlator, current VLBI technology work is focusing on VLBI data systems for the future. The Mark 5 disc-based data system is well along in development and will enter field operation in 2002; approximately 20 Mark 5 units are expected to be deployed. In addition, the Mark 5 system will be used in a demonstration of ~1 Gbps electronic transmission of VLBI data over an IP network between Haystack Observatory (Westford, MA) and NASA/GSFC, a distance of ~700 km.

Mark 4 Correlator

Mark 4 correlators have become operational at USNO, MPI, JIVE and Haystack for about two years and have now completely replaced all Mark III and Mark IIIA correlators. Over the last year, significant enhancements have been made to Mark 4 correlator software to improve operational flexibility and efficiency. Among the most important are: multiple-stream processing (up to four simultaneous independent scans), faster tape synchronization (typically <5 seconds), and 'Double-speed' tape playback. The Mark 4 correlator is now designated as 'mature', but enhancements planned over the next year include: support of Mark 5 VLBI data system, increase to 8 playback systems, 'Quadruple-speed' playback speed, and refinement of the baseline phase model.

Mark 5 VLBI Data System

In early 2001, a demonstration Mark 5 system, shown in Figure 9, was developed and tested. This system has the following characteristics: built entirely of COTS components for ~$25K. Based on standard PC platform, maximum data rate of 512 Mbps to 16 discs, recorded data directly from a Mark 4 formatter, and data reproduced into a Mark 4 correlator for correlation.

In March 2001, this demonstration system was used to record VLBI data at Westford Observatory at 256 Mbps, which was successfully correlated against Mark 4 tape data recorded at NASA/GSFC on the Mark 4 correlator at Haystack Observatory.

Figure 9: Demonstration Mark 5 System

Based on the success of the Mark 5 demonstration unit, NASA (under contract with Haystack Observatory) is now undertaking the development of an operational 1 Gbps Mark 5 system with support from other cooperating partners: BKG, KVN, MPI, JIVE, NRAO and USNO.

The Mark 5 system is being developed in three stages:

1. Mark 5P: Records and replays 32 Mark4/VLBA tracks. The Mark 5P is primarily a test platform for the disc interface board that is being developed for the Mark 5 project by Boulder Instrument, Inc. of Longmont, CO.

2. Mark 5A: Records 8, 16, 32 or 64 tracks from a Mark4/VLBA formatter, up to 1024 Mbps (parity stripped), and plays back in the same Mark4/VLBA format. Direct replacement for Mark4/VLBA tape drives. Expect deployment of ~20 systems late spring 2002.

3. Mark 5B: VSI-compliant system, up to 1024 Mbps; no external formatter necessary. Will be backwards compatible to existing Mark4/VLBA correlator systems. Expect to deploy late 2003.

e-VLBI Development

NASA and DARPA are supporting Haystack Observatory to demonstrate 1-Gbps e-VLBI over a standard IP-based network between Haystack Observatory and NASA/GSFC. The Westford antenna at Haystack Observatory will be used in conjunction with the GGAO antenna at NASA/GSFC. Data will be transmitted in real-time from both antennas to the Mark 4 correlator at Haystack Observatory for correlation.

Part of the network path will be over standard U.S. science network infrastructure, where other users share the network links and the data must traverse many routers and switches. Part of the purpose of this test is to determine the real throughput of these networks under stressful shared conditions. Tests between Haystack Observatory and the Westford have already demonstrated sustained data rates of ~980 Mbps over standard Gigabit Ethernet links through several switches, and we expect to achieve similar rates over the 700 km link between Haystack and NASA/GSFC. The full demonstration is scheduled for late spring 2002.

If these demonstrations are successful, we intend to seek support to extend Gbps e-VLBI to other sites within the U.S. as well as overseas to Europe and Japan. Currently, intensive work is now in progress in cooperation with NASA/GSFC, U. Maryland, MIT Lincoln Laboratory, as well as technical experts at MAX and ISI-E, to upgrade and test the e-VLBI path. Portions of the link have been tested, and the entire link is expected to be operational by late February 2002 at which time testing with VLBI data will begin.

NASA's VLBI Observatories

Gilmore Creek Geophysical Observatory

Gilmore Creek Geophysical Observatory (GCGO) is located 22 km Northeast of Fairbanks, Alaska. The observatory is co-located with the NOAA weather satellite command and data acquisition station. The station sits on an 8,500-acre reservation that is mostly undeveloped wilderness. The GCGO is part of the NASA Space Geodesy program in cooperation with the U.S. Naval Observatory. The antenna used for VLBI is a 26-meter telescope which is hydraulic operated and controlled by a Modcomp computer system. The DAT rack is a VLBA terminal and recorder (thin tape). The X/S band microwave receiver has a cryogenic low noise front end.

Kokee Park Geophysical Observatory

Kokee Park Geophysical Observatory is located on the Island of Kauai in the Hawaiian Islands. The site is in Kokee State Park, located at an elevation of 1100 meters near the Waimea Canyon, which is often referred to as the Grand Canyon of the Pacific. NASA's partner, USNO, built the current 20-meter antenna. Kokee is an essential site for the USNO Intensive Schedule. The receiver is of NRAO (Green Bank) design (dual polarization feed using cooled 15 K HEMT amplifiers). The antenna is of the same design and manufacture as those used at Green Bank and Ny Alesund.

Goddard Geophysical and Astronomical Observatory

The Goddard Geophysical and Astronomical Observatory consists of a radio telescope for VLBI, SLR site to include MOBLAS-7, SLR-2000 (development system), a 48" telescope for developmental two color Satellite Ranging, a GPS timing and development lab, meteorological sensors and a H-maser. In addition, we are a fiducial IGS site with several IGS / IGSX receivers. The radio telescope for VLBI at GGAO (MV3), originally built as a mobile or transportable station, is used as a NASA R&D and data collection facility.

Figure 10. Map showing the components of the IVS.

Calibration Facility

The Calibration Facility provides calibrated sources of spectral radiance in the wavelength interval 0.4 µm (violet) to 2.5 µm (short wave infra-red), and at intensities including dark scenes such as sunlit sea surface, bright scenes such as sunlit cloud tops, and higher intensities for calibrating sun photometers and spectrometers. The emission spectrum of one of our sources, at maximum intensity, is shown in Figure 11 together with two comparison spectra. The nadir spectrum above the atmosphere for an early summer noon at White Sands desert, New Mexico, as computed by the MODTRAN program for a surface albedo of 60%, illustrates the magnitude of spectral radiances expected from terrestrial scenes. It also shows the effects of atmospheric absorption bands. The second spectrum, that of a sun-illuminated perfect diffuser above the atmosphere, illustrates the complex spectral structure of the solar spectrum, some of which can be seen repeated in the calculated White Sands spectrum.

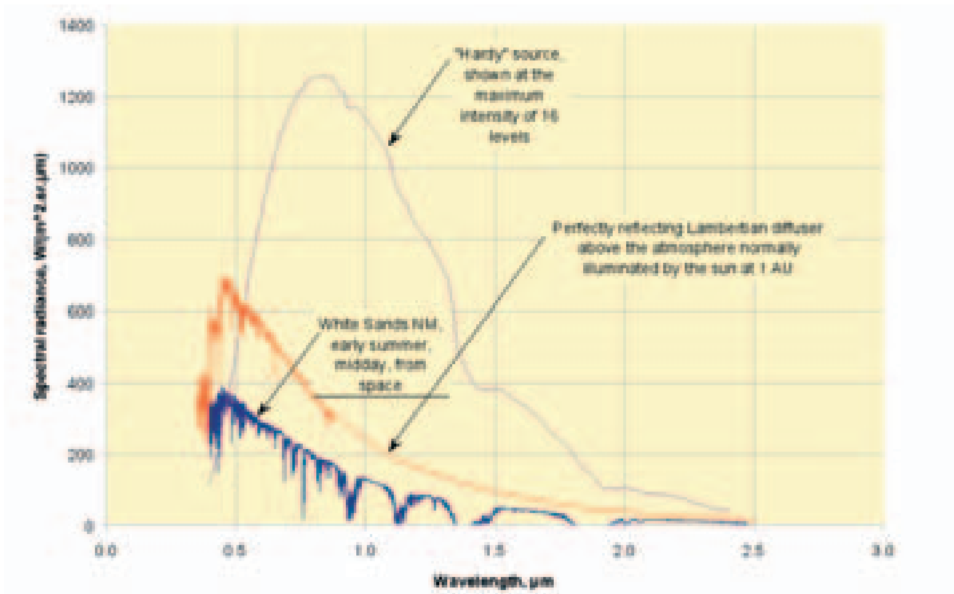

Figure 11: The 2 m diameter "Hardy" source at maximum radiance, shown with the computed spectrum above White Sands NM (assumed albedo = 60%) at noon on an early summer day, and the spectral radiance of a perfect diffuser above the atmosphere aligned perpendicular to the solar vector.

Figure 12 is a photograph of "Hardy", the largest (1.8 m diameter) and most intense of our sources, together with its power supply and data collection console. A ring of tungsten halogen lamps inside the source, behind the wire harness visible in Figure 12, is driven by a set of DC power supplies, with the current stabilized to better than ± 0.01%. This level of stabilization is necessary to reduce the corresponding changes in spectral radiance at the most sensitive wavelength (400 nm) to less than ± 0.1%. Barium sulfate paint, containing a small amount of polyvinyl alcohol as a binder, coats the interior surfaces of the source. This material is highly reflecting at wavelengths below 1 µm, resulting in a large number of diffuse reflections for those photons emitted from the lamp filaments that successfully exit through the source aperture. Consequently, spectral radiance uniformity across the 25 cm diameter exit aperture is better than ± 0.2% for wavelengths below 1 µm, and is almost as uniform at higher wavelengths.

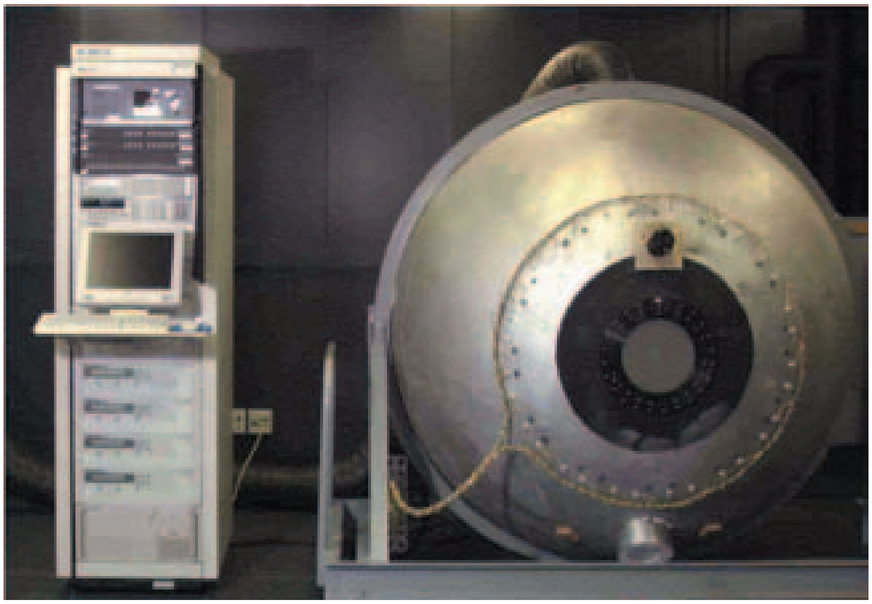

Figure 12: The 2 m diameter "Hardy" source with its power supply and data system console. The source aperture, defined by the circle within the black circle on the sphere, is 25 cm diameter.

Sources are calibrated approximately every month relative to a NIST standard irradiance lamp. This procedure is necessary to offset slow degradation in radiance output caused by aging of the lamps within the source and the barium sulfate paint (usually a few percent per annum). With the wealth of supporting information collected on temperature, humidity, lamp voltages and lamp usage times, etc., we hope to build a predictive ability for identifying lamps and other components in the early stages of failure and to forecast changes in spectral radiance.

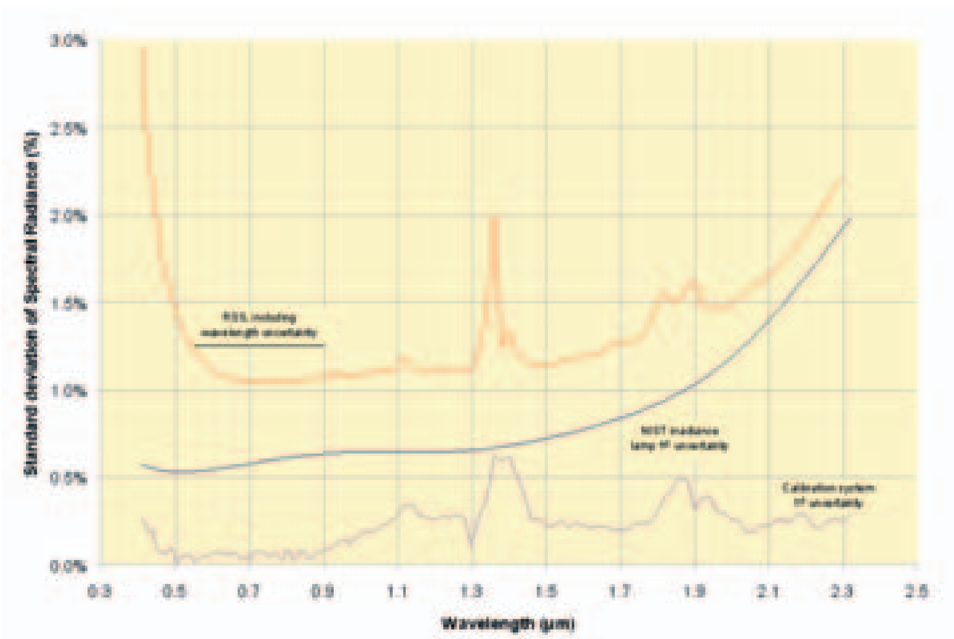

Figure 13: The total one-sigma uncertainty for calibration of the "Hardy" source, showing its principal components.

Figure 13 illustrates the uncertainties we believe remain after one of our sources has been calibrated. The dominant components of the uncertainty budget are uncertainty in the spectral irradiance of the NIST standard lamp, uncertainty in the spectral calibration of our transfer spectrometer (especially at short wavelengths), and uncertainty in the measurement of the solid angle used to convert the NIST spectral irradiance to source spectral radiance. Other, relatively minor, components of the uncertainty budget include noise in the spectrometer system and lamp current uncertainty. Short-term changes in responsivity of our spectrometer system are believed to be negligible, but remain to be determined.

The Calibration Facility maintains several sources, each intended for a particular range of activities. Our 1.2 m diameter hemisphere source ("Laurel") is particularly useful when large diameter exit apertures are required, or when laboratory space is limited. Laurel has been used, for example, to assess the uniformity of response of the EPIC camera system on the Triana spacecraft. This work, completed in 2000, required an unusually large source diameter of over 45 cm. Another popular source, identified as "Slick", uses internal plates of polytetrafluoroethylene (PTFE) to scatter light emitted by the lamp filaments. PTFE is preferable to barium sulfate in that it contains negligible amounts of water and it has a higher reflectivity beyond a wavelength of 1µm. Slick has been most recently used in our laboratory to calibrate spectrometers for the SAFARI expeditions to South Africa, SIMBAD instruments for project SIMBIOS (Sensor Intercomparison and Merging for Biological and Interdisciplinary Ocean Studies), and for AERONET (AErosol RObotic NETwork) sun photometer calibrations. Occasionally the sources themselves travel to sites around the world. In recent years Calibration Facility staff and equipment have advanced NASA field programs in Portugal, Brazil, Japan and Canada, as well as many American states.

The Calibration Facility usually houses its radiance sources in class M 5.5 clean rooms, implying that the density of airborne particles with a diameter of 0.5µm or greater is less than $10^{5.5}$, or 353,000 per cubic meter. The clean room air within the sources is further controlled in temperature and humidity. The Calibration Facility uses its sources to calibrate aircraft and space instruments containing sensitive optics, such the Shuttle Ozone Limb Sounding Experiment.

The Calibration Facility's primary source calibration instrument is an Optronic Laboratory model 746 monochromator with an integrating sphere irradiance collector (746/ISIC). The 746/ISIC is calibrated in irradiance response prior to each measurement using a 1000 W quartz-halogen standard irradiance lamp that is traceable to NIST irradiance standards, and in wavelength using conventional line source lamps and lasers. Using silicon photodiode and lead sulfide detectors, the 746/ISIC transfers the irradiance calibration from the standard lamp to the sphere source being measured. Knowledge of the aperture areas of the sphere under test and the ISIC collection sphere coupled with a measurement of the distance between the two apertures enables the radiance of the sphere source to be calculated. In the visible/near infrared wavelength region from 400 nm to 1000 nm, the 746/ISIC obtains data in 10 nm steps with a bandwidth of 10 nm. In the short-wave infrared wavelength region from 1000 nm to 1600 nm, data is obtained every 20 nm with a bandwidth of 20 nm. In the wavelength region from 1600 nm to 2500 nm, data is obtained every 20 nm with a bandwidth of 40 nm.

Although the primary customers of the Calibration Facility directly support the EOS Project, anyone interested in using the Calibration Facility is encouraged to contact our group. Provided the proposed work advances NASA's interests, we will be delighted to provide calibration services on a time-available basis and negotiable cost. Our website address is www.spectral.gsfc.nasa.gov, which we share with the Diffuser Calibration Facility.

The Calibration Facility moved into its present location in Building 33 in February, 1999, and since that time has concentrated on improving communication with the user community through its website and improving the performance of its radiance calibration source systems, particularly in the areas of stabilizing lamp currents, continuous monitoring of critical system parameters such as lamp current and ambient temperature, independently monitoring source spectral radiance at selected wavelengths, controlling internal source air temperature and humidity, and improving data handling and remote control hardware and software.

In April, 2001 the Calibration Facility hosted the twelfth "Round Robin" EOS Radiometric Measurement Comparison Campaign, bringing together groups from NIST, NASA's GSFC and Ames Research Center, the universities of South Dakota and Arizona, and Research Support Instruments, Inc., to evaluate the performance of Hardy and to use it to compare the performance of radiometric sources and sensors provided by the different groups. High spectral radiance uniformity across the exit aperture of Hardy was necessary for the comparisons, and the uniformity was measured to be better than ±0.5%. A newly constructed 9-band filter radiometer for monitoring the spectral radiance from Hardy was completed in time for the comparison campaign. It was used to investigate radiance changes during warm-up, and gave results that were confirmed by independent NIST measurements. Results from the Comparison Campaign are presented more fully in the EOS Calibration section.

An Optronic Laboratory model 750 monochromator system has been refurbished with new motors, chopper, electronics and data system. The 750 system is intended as a back-up to the Optronic Laboratory model 746 monochromator system currently used to calibrate all our sources. When the 750 system has completed planned test and evaluation phases it will allow the 746 system to be taken off-line after more than a decade of uninterrupted service.

A source at NASA's Ames Research Center, used in the calibration of airborne instruments, was re-calibrated by Calibration Facility staff in May, 2001. Re-calibration is usually repeated at the request of NASA Ames staff at approximately annual intervals.

An environmental control system for Hardy, intended to control the temperature and humidity of air re-circulated within the source, is in the final stages of assembly.

User groups for Calibration Facility services in 2001 are shown in Table 4.

Table 4: Customers of the Calibration Facility in 2001

Project	Instruments	Customers
AErosol RObotic NETwork (AERONET) Penn State University Meteorology Department	Cloud sun photometers	Code 923 Penn State University
Sensor Intercomparison and Merging for Biological and Interdisciplinary Ocean Studies (SIMBIOS)	SeaWiFS transfer spectrometer Sensor Integration and Modeling for Biological Agent Detection (SIMBAD) radiometers	Code 970.2 Code 971.2
Earth Observing-1 satellite (EO-1)	Linear Etalon Imaging Spectrometer Array (LEISA)	Code 693
	Analytical Spectral Devices (ASD) spectrometers	Codes 913, 923, 935 South Dakota State University NASA's Langley Research Center
	[illegible] (an 80 cm diameter hemispherical source)	Code 923
Shuttle Ozone Limb Sounding Experiment (SOLSE-2)	SOLSE-2	Code 916
	Cloud Absorption Radiometer (CAR)	Code 913
Triana	Triana's Earth Polychromatic Imaging Camera (EPIC)	Code 443
EOS Radiometric Measurement Comparison Campaign	Visible Transfer Radiometer (VXR) Short Wave Infrared Transfer Radiometer (SWIXR) Ultra Violet Filter Radiometer (UVFR) Ultra Violet Scanning Radiometer (UVSR) Ultra Violet Filter Radiometer (UVFR) Ultra Violet Scanning Radiometer (UVSR) VNIR, SWIR Analytical Spectral Devices (ASD) spectrometer Ocean Optics Spectrometer Landsat Transfer Radiometer Calibration Transfer Standard Spectrometer	NIST University of Arizona University of South Dakota Code 923 Research Support Instruments, Inc

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Diffuser Calibration Facility

The Diffuser Calibration Facility (DCaF) has operated within Code 920 since May 1993. The facility is a class 10,000 cleanroom and contains a unique, state-of-the-art, out-of-plane optical scatterometer. This scatterometer is capable of measuring the bi-directional scatter distribution function (BSDF) of transmissive or reflective, specular or diffuse optical elements and surfaces in addition to granular, powdered, or liquid samples. (BSDF is a term which includes bi-directional reflective and transmissive distribution function measurements (i.e. BRDF and BTDF).) The facility is considered a secondary standards calibration facility with measurements directly traceable to the Spectral Tri-function Automated Reflection Radiometer (STARR) located at the National Institute of Standards and Technology (NIST) in Gaithersburg, Maryland. BSDF measurements are made at any incident and scatter angle above or below a sample. The scatterometer employs incoherent and coherent monochromatic light sources. The incoherent source is a xenon arc lamp and 0.25 m Czerny-Turner monochromator. The current operating wavelength range of this source is 230 to 900 nm with an adjustable bandwidth between 4 and 10 nm. The coherent sources include He/Ne lasers at 543.5, 594.1, 612.0, and 632.8 nm and a He/Cd laser at 325.4nm. The scatterometer is capable of polarized or unpolarized measurements using all sources. The sample stage can support samples up to 12 inches on a side and weight up to 10 lbs. Samples can also be rastered for reflectance or transmittance uniformity. Scatterometer receivers include uv-sensitive and visible silicon photodiodes and photomultiplier tubes. The data acquisition electronics include programmable preamps matched to each detector and a programmable dual channel lock-in amplifier. The scatterometer is completely automated and data is displayed in real time. The DCaF is in the process of commissioning dedicated hardware to enable the rapid, direct measurement of 8 degree directional/hemispherical scatter of reflective samples. This measurement will complement and validate the current approach of integrating BRDF over the complete scattering hemisphere of a sample to determine hemispherical scatter.

The measurement uncertainty of DCaF BSDF measurements is 0.7% (k=1), and agreement between absolute BSDF measurements made by the DCaF and by NIST on identical samples is 1% or better over the complete wavelength operating range of the scatterometer. The current measurement uncertainty of DCaF directional hemispherical measurements is 1% (k=1) over the complete operating wavelength range.

Since 1993, the DCaF has literally made tens of thousands of scatter measurements for flight and non-flight projects from both the government and private sectors. DCaF customers are summarized below.

In calendar year 2001, the DCaF continued to provide scatter measurements to a number of flight and non-flight projects in accordance with established flight and deployment schedules.

Solar Backscatter Ultraviolet-2 (SBUV-2) BRDF Calibrations

Since 1993, the DCaF has measured the BRDF of the Spectralon diffusers used in the pre-launch calibration of the Shuttle Solar Backscatter Ultraviolet-2 (SBUV-2) instruments producing a long-time series reflectance calibration dataset. In 2001, SBUV-2 Spectralon calibration diffusers H1 and H2 were measured at 13 ultraviolet wavelengths between 230 nm and 425 nm (Figure 14).

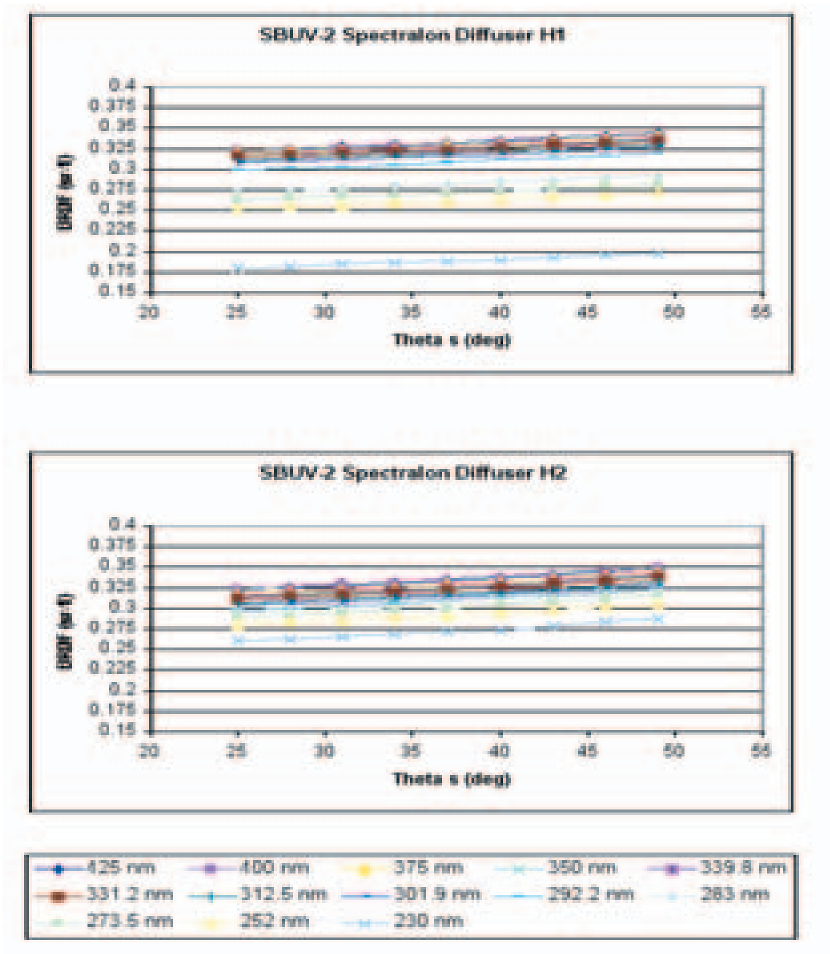


Figure 14. Unpolarized BRDF measurements on SBUV-2 Spectralon diffusers H1 and H2. These diffusers are used in the prelaunch calibration of the NOAA 14 and NOAA M SBUV-2 instruments. Note that the reflectance of diffuser H1 below 283nm is significantly less than that for H2.

Code 916 BRDF Calibrations:

Also since 1993, the DCaF has measured the BRDF of barium sulfate and Spectralon diffusers which were used in the calibration of the Shuttle Solar Backscatter Ultraviolet (SSBUV) instrument. They are currently used in the calibration of the Code 916 Shuttle Ozone Limb Sounding Experiment/Limb Ozone Retrieval Experiment (SOLSE/LORE) and in prelaunch reflectance measurement comparisons of the Ozone Monitoring Instrument (OMI) scheduled for launch on EOS Aura. In 2001, Spectralon diffusers H4 and H5 were measured in the DCaF at 13 ultraviolet wavelengths from 230nm to 425nm.

BRDF Calibrations in Support of NOAA SIMBIOS Validation

In 2001, the DCaF made scatter measurements for a number of new customers. In 2001, the DCaF made visible and near infrared BRDF measurements on 3 gray-scale Spectralon diffusers used in shipboard validation studies of ocean remote sensing satellite instruments for the National Oceanic and Atmospheric Administration (NOAA). This project is funded through NASA's Sensor Intercomparison and Merger for Biological and Interdisciplinary Oceanic Studies (SIMBIOS) program (Figure 15).

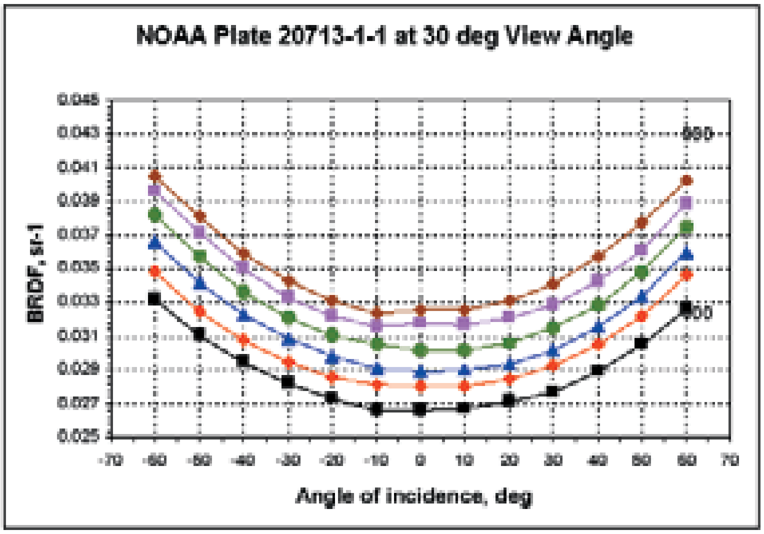


Figure 15. Unpolarized BRDF of a NOAA gray-scale Spectralon diffuser used in SIMBIOS validation studies. These data were acquired at an incident angle of 30 degrees from the diffuser normal and over a scatter angle range of –60 to +60 degrees. The data were acquired from 400 nm (black squares) to 900 nm (brown diamonds) in 100 nm steps.

BRDF Measurements in Support of the GLAS Project

In 2001, the Geoscience Laser Altimeter System (GLAS) project was also a new customer of the DCaF. The DCaF determined the amount of light exiting a beam dump designed to be used to efficiently capture light from the GLAS laser (Figure 16).

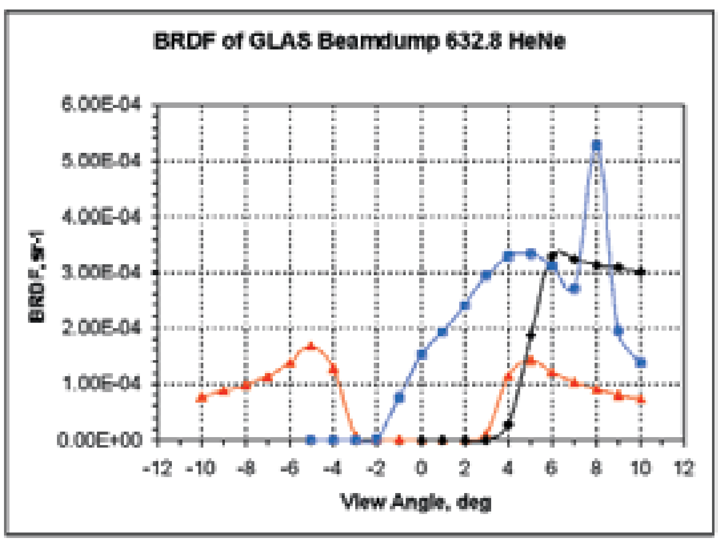


Figure 16. BRDF measurements on a protype GLAS laser beam dump. The red points are data acquired over a scatter angle range of –10 to +10 degrees with light introduced at normal incidence to the beam dump. The decrease in the data between –5 and +5 degrees is due to the scatterometer detector being located behind a fold mirror. The black points are data acquired over a scatter angle range of 0 to +10 degrees and in a direction 90 degrees orthogonal to the red points. The blue points are data acquired over a scatter angle range of –5 to +10 degrees with light introduced into the beam dump at 5 degrees from normal incidence. Note the strong forward scatter in these data and the interesting peak at 8 degrees scatter.

In addition to the beam dump measurements, several BRDF measurements were made for the GLAS project on roughened and smoothed black graphite composite materials. These data were used by the GLAS project in the assessment of stray light issues (Figure 17).

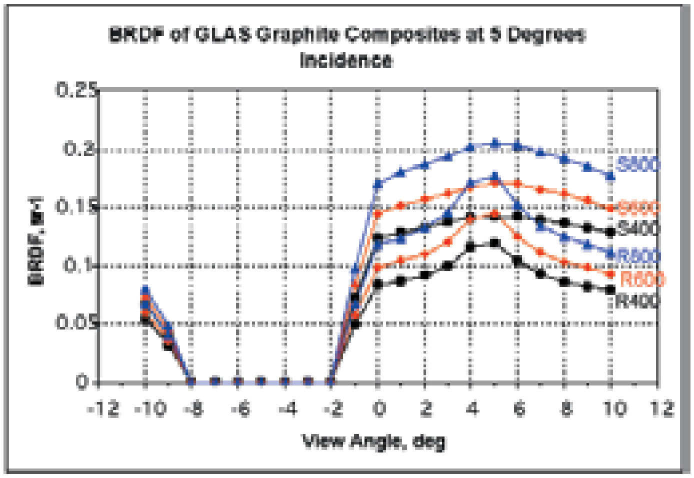


Figure 17. BRDF measurements at -5 degrees incidence on smooth (S) and roughened (R) black graphite composite samples provided by the GLAS project. The measurements were made at 400 nm (black circles), 600 nm (red diamonds), and 800 nm (blue triangles) over a scatter angle range of –10 to +10 degrees. Note that the specular peak in the BRDF curve at +5 degrees scatter is more pronounced for the roughened sample than the smooth sample.

BRDF Measurements of Solar Panels in Support of the NRL FAME Project

In 2001, the Naval Research Laboratory (NRL) requested that the DCaF perform BRDF measurements from the visible to near infrared on solar panel samples and aluminized Kapton, black Kapton, and silver-coated Teflon samples for their Full-sky Astrometric Mapping Explorer (FAME) project. The initial design for the FAME spacecraft was to use solar radiation to control spacecraft attitude control. The purpose of these measurements was to characterize the directional reflectance of these materials on the FAME spacecraft in an effort to estimate the momentum transfer from incident solar photons. These measurements were successfully used by NASA's GSFC and Swales Aerospace to predict the momentum imparted to these materials from the force of incident solar photons (Figure 18).

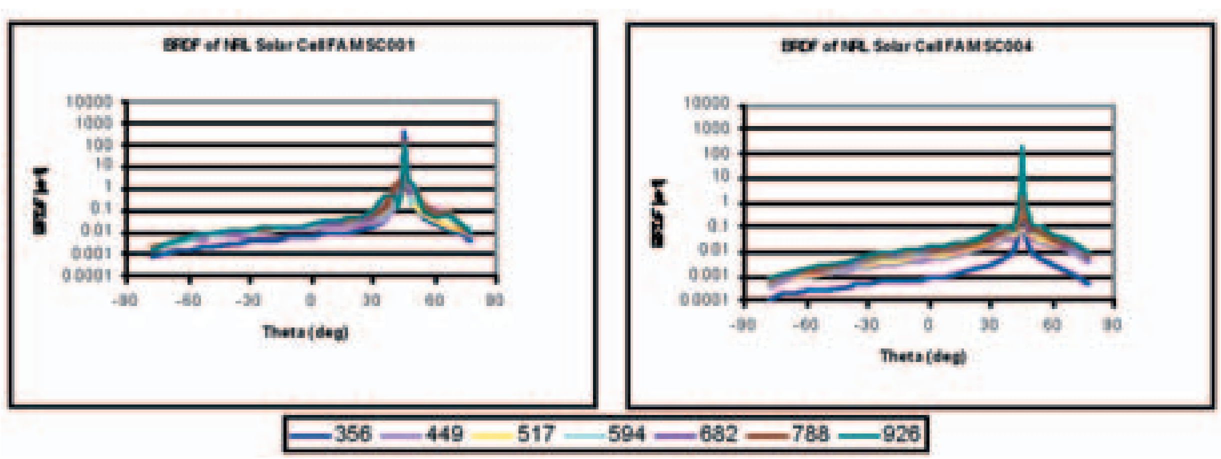
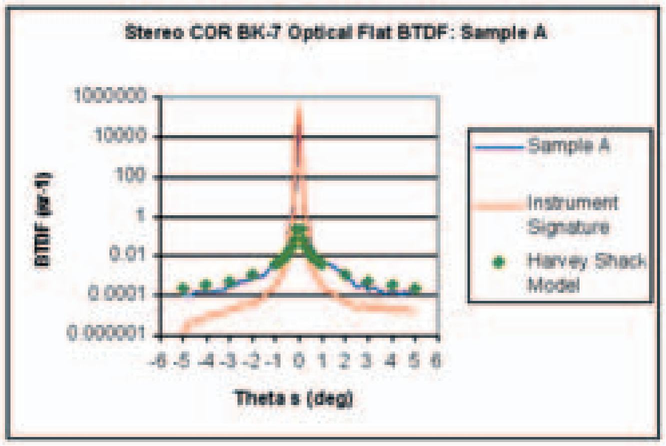


Figure 18. Specular, unpolarized BRDF of two NRL solar panel samples obtained from the NRL FAME project. These data were acquired at 45 degrees incidence and over a scatter angle range of –78 to +78 degrees at 7 wavelengths between 356 nm and 926 nm.

BTDF Measurements on Stereo COR-1 Optical Flats

In 2001, the Code 682 Solar Physics Branch requested that the DCaF make BTDF measurements on 12 BK7 optical flats for the Stereo Coronagraph –1 (COR-1) project. These flats were polished to an average surface roughness of 3 Angstroms and were the same material as the front objective lens of the COR-1 satellite instrument. The plan was for the DCaF to make BTDF measurements before and after controlled, laboratory exposure of the optical flats to solar wind-like conditions. The initial BTDF measurements on the optical flats at 1 degree from the transmitted beam agreed well with the predictions of a Harvey Shack model (Figure 19).



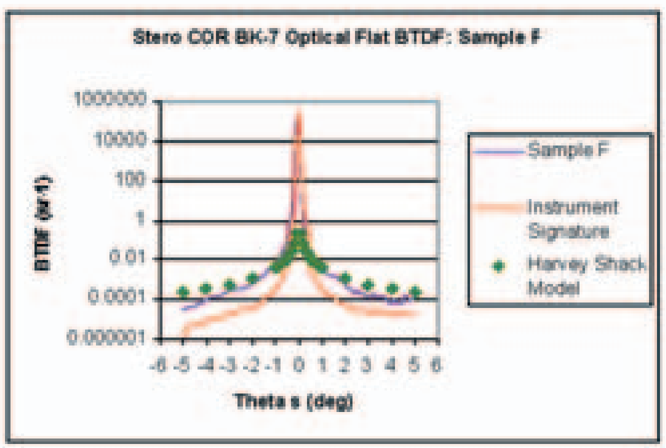


Figure 19. BTDF of two BK-7 optical flats obtained from the COR-1 solar physics project. These data were obtained at normal incidence to the flats over a scatter angle range of –6 to +6 degrees. The Harvey Shack model predicts a BTDF of 2E^{-3} sr^{-1} at 1 degree from the transmitted beam for an optical flat with 3 Angstroms surface roughness. The model prediction is supported by the BTDF data from these samples.

Future Work:

The scatter measurement capabilities of the DCaF are currently being expanded in a number of areas. First, a directional hemispherical measurement capability is being implemented to complement and validate the current directional hemispherical measurement approach of integrating BRDF over the complete scattering hemisphere of a sample. Second, the operational wavelength capability of the DCaF will be expanded from 900nm to 2500nm. This measurement capability is currently being breadboarded and tested in the Code 920.1 Engineering Laboratory. Third, a vacuum system has been constructed which will be used in materials testing studies. These studies will include controlled exposure of spaceflight diffusers, mirrors and lenses to the output of a solar simulator both in the presence and absence of contaminants followed by BSDF measurements.

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EOS Calibration

The Earth Observing System (EOS) is an 18-year, international multi-satellite program in global remote sensing of the Earth. As such, EOS is and will continue to be the fundamental source of satellite data on the earth and its environment into the 21st century. The overall goal of the EOS mission is to advance the scientific understanding of the entire earth system and its changes on a global scale through the development of a deeper understanding of the components of that system and their interactions. In order to achieve those goals, EOS has and will continue to produce global, long-time series, remote-sensing data sets from multiple instruments on several satellite platforms. The correct interpretation of scientific information from these data sets requires the ability to discriminate between on-orbit changes in the instruments and changes in the earth physical processes being monitored. The ability to make this distinction depends crucially on the calibration of the instruments with respect to a set of recognized physical standards or processes, the careful characterization of the instruments' performance at the subsystem and system levels, the cross-calibration of the instruments, and the post-launch validation of the instruments fundamental radiance and reflectance products.

The Space Geodesy Networks & Sensor Calibration Office provides technical and administrative support to the EOS Project Science Office in the calibration of satellite, airborne, and ground-based instruments. This includes coordinating and participating in satellite instrument reviews, participating in algorithm theoretical basis document (ATBD) reviews, coordinating and participating in measurement assurance programs (MAPS) with the assistance of NIST, and providing over-arching technical guidance in the EOS lunar photometry project underway at the United State Geological Survey in Flagstaff, Arizona.

Ultra-violet, Visible, Near and Shortwave Infrared Radiometric Measurement Comparison at GSFC

From March 30 through April 9, 2001, thirteen radiometers participated in a radiometric measurement comparison at the National Aeronautics and Space Administration's Goddard Space Flight Center (NASA's GSFC). Table 5 lists these radiometers, comparison participants with institutional affiliations, operating wavelengths, and measurement uncertainties. These radiometers made measurements from the ultraviolet through the shortwave infrared wavelength regions on four sources of uniform radiance. These sources included the NIST Portable Radiance Source (NPR) (Brown and Johnson 1999), the GSFC Code 920.1 180cm diameter integrating sphere known as Hardy, the GSFC Code 916 50.8cm diameter integrating sphere, and a Spectralon™ panel illuminated by two NIST irradiance standard lamps.

The GSFC radiometric measurement comparison was held in the Code 920.1 class 10,000 clean-room Radiance Calibration Facility. The goals of the comparison were (1) to validate the radiance scales assigned to the Hardy and Code 916 50.8cm spheres by Codes 920.1 and 916, respectively, (2) to critically examine the Code 916 and 920.1 sphere operation and sphere radiance repeatability and stability, and (3) to validate the radiance measurements of a number of radiometers used in the vicarious calibration of fundamental EOS satellite instrument measurements. Figure 20 shows preliminary comparison results obtained from participating radiometer measurements of the Code 916 and Hardy sources, respectively. The GSFC Code 920.1 Radiance Calibration Facility, the GSFC Code 916 Radiometric Calibration and Development Facility, and the Ames Airborne Sensor Facility Sensor Calibration Laboratory play prominent roles in the calibration of Earth Observing System (EOS) satellite, vicarious calibration, and validation instruments. The radiometric comparison at GSFC effectively complements the previous comparison held at NASA's Ames in August/September 1999.

Table 5. Radiometers Participating in the GSFC Radiometric Measurement Comparison

Radiometer	Institutional Affiliation	Responsible Person	Operating Wavelengths (nm)	Measurement Uncertainty (k=1)
Visible Transfer Radiometer (VXR)	NIST/EOS	Carol Johnson	411.8, 441.0, 548.4, 661.4, 775.5, 870.0	1.2% at 411.8nm 0.7% at 775.5nm
ShortWave Infrared Transfer Radiometer (SWIXR)	NIST/EOS	Steve Brown	800 to 2400	1.7%
Ultraviolet Scanning Radiometer (UVSR)	NIST	Ted Early	300 to 400	
Ultraviolet Filter Radiometer (UVFR)	NIST	David Allen	317.7, 325.1, 339.9, 388.0, 393.4	1.75%
U. of Arizona Visible/Near Infrared Radiometer (UAVNIR)	U. of Arizona	Stuart Biggar	412.8, 441.8, 488.0, 550.3, 666.5, 746.9, 868.1	2.1% at 412.8nm 2.2% at 666.5nm
U. of Arizona ShortWave Infrared Radiometer (UASWIR)	U. of Arizona	Ed Zalewski	746.9, 868.7, 940.0, 1243.5, 1380.8, 1646.0, 2133.5, 2164.2, 2207.8, 2262.9, 2332.2, 2402.9	3.9% at 900nm 3.9% at 1300nm 3.9% at 1600nm 3.5% at 2000nm 3.9% at 2400nm
Landsat Transfer Radiometer (LXR)	NASA's GSFC	Brian Markham Milton Hom Ed Kaita	480.7, 440.0, 560.7, 661.1, 662.3, 827.0	
746 Integrating Sphere Irradiance Collector (746/ISIC)	NASA's GSFC	John Cooper	400 to 2400	1.94% at 400nm 1.56% at 1000nm 2.22% at 2200nm
South Dakota State University Analytical Spectral Devices field radiometer (SDSU ASD)	South Dakota State University	Steven Schiller	350 to 2500	
GSFC Analytical Spectral Devices field radiometer (GSFC ASD)	NASA's GSFC	Brian Markham Milton Hom Ed Kaita	350 to 2500	
SeaWiFS Transfer Radiometer II (SXR II)	NASA's GSFC	Gerhard Meister	410.7, 441.5, 487.6, 546.9, 661.9, 776.7	1.2% at 410.7nm 0.9% at 776.7nm
Calibration Transfer Standard Radiometer (CTSR)	Research Scientific Instruments	Don Heath	302.2, 305.6, 318.0, 321.6, 325.1, 339.7, 345.2, 437.5, 439.2, 525.0, 600.0, 674.6, 760.3, 923.8, 935.1	
Ames Analytical Spectral Devices field Radiometer (Ames ASD)	NASA's Ames	Pavel Hajek	350 to 2500	

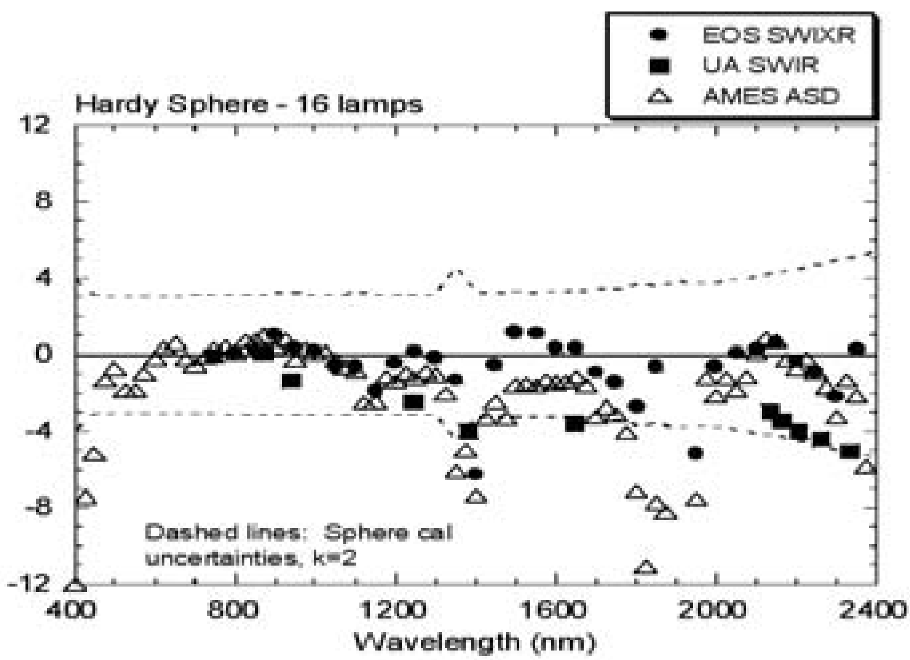

Figure 20. Percent difference of 16 lamp Hardy sphere measurements made by the shortwave infrared transfer radiometers and the Ames ASD from the GSFC 746/ISIC measured radiances.

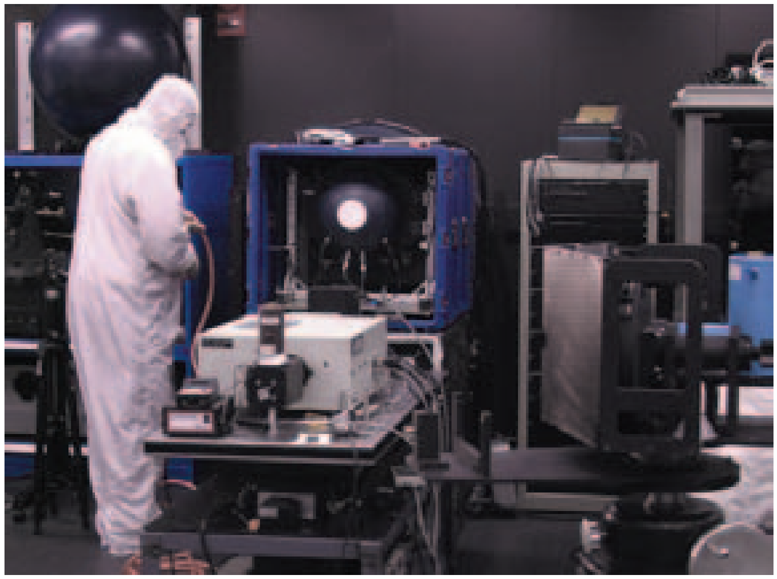

Figure 21. Steve Brown (NIST) preparing the NIST/EOS ShortWave Infrared Transfer Radiometer (SWIXR) for measurements on the NIST Portable Radiance (NPR) Source during the April 2001 radiometric measurement comparison at GSFC. The University of Arizona ShortWave Infrared Radiometer (UASWIR) is seen in the right foreground of this photo.

Infrared Measurement Comparison at the University of Miami

On May 31 and June 1, an infrared radiometric measurement comparison was held at the University of Miami's Rosenstiel School of Marine and Atmospheric Science. During the comparison, the NIST EOS Thermal Transfer Radiometer (TXR) made radiance measurements of the University of Miami's Water Based Blackbody (WBBB), the NIST WBBB, the University of Washington's vertically configured blackbody, and two blackbodies used in the European Commission Joint Research Center's Combined Action for the Study of the Ocean's Thermal Skin (CASOTS) project. In addition, the NIST WBBB was made available to a number of infrared radiometers used in the validation of satellite ocean temperature measurements.

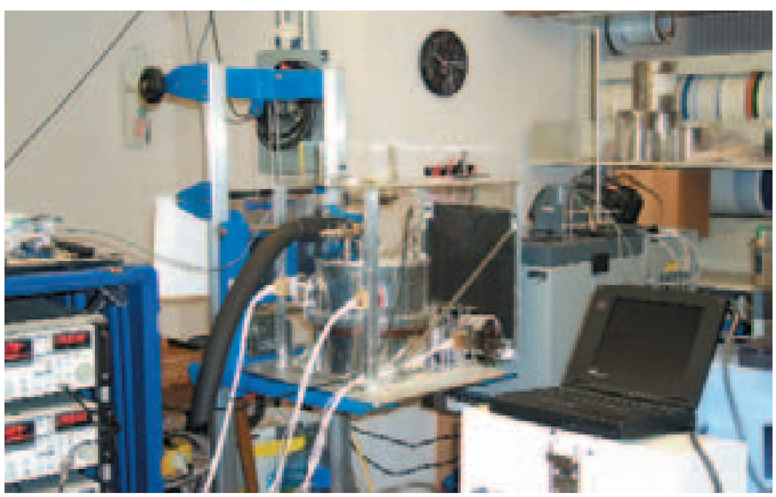

Figure 22. The NIST/EOS Thermal Transfer Radiometer (TXR) measuring the infrared radiance emitted from the water based blackbody used in the pre- and post-deployment calibration of the University of Miami's Marine Atmospheric Emitted Radiance Interferometers (M-AERIs).

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MODIS Calibration Support Team (MCST)

The MODIS Characterization Support Team (MCST) was formed by Dr. Vincent Salomonson, MODIS Science Team Leader, as a major element in the development, characterization and operation of the Moderate Resolution Imaging Spectroradiometer (MODIS). MODIS has been described as the "keystone sensor" on the EOS/Terra and EOS/Aqua satellites. MCST has three major responsibilities. It must characterize the Terra and Aqua sensors both pre- and post-launch; it is responsible for the development and maintenance of the Level 1B (L1B) radiometric calibration algorithm; and, finally, the team is charged with the day-to-day operation of both sensors.

MCST's characterization function was initiated during the early sensor design period and will continue through the life of the missions. Initially, this task consisted of supporting the Instrument Systems Manager of the Terra and Aqua Projects during the sensor development phase. During the testing phase, MCST analyzed large volumes of data acquired during extensive ambient and thermal-vacuum testing. Results from these analyses served to define and develop the L1B algorithm.

The L1B development task has resulted in over 8000 lines of code that accept input from the Level 1A (L1A) geometrically located MODIS data and outputs the L1B product consisting of radiometrically calibrated and geometrically located pixels for all 36 of the MODIS spectral bands. In addition to applying data from the pre-launch and on-orbit calibration measurements to the sensor data, the software must account for numerous sensor characteristics such as spectral and spatial response, temperature sensitivity, electrical and optical cross-talk and time-dependent changes degradation. Changes in operational parameters are accommodated via large look-up tables (LUTs). New LUTs must be generated each time the sensor operational configuration is changed and must be stored for future reprocessing efforts.

A sub-set of the MCST is the Instrument Operations Team (IOT). This group is responsible for monitoring and generating commands for both MODIS sensors. This is a 24/7 task that requires careful attention to detail and a good understanding of both the sensors and the spacecraft on which they reside.

The Terra spacecraft was launched on December 18,1999 and the Aqua spacecraft will be launched during the spring of 2002. During 2001, MCST has had several major accomplishments, including the successful characterization of solar diffuser (SD) degradation and development of a time-dependent calibration approach for the reflective solar bands. This progress was applied and implemented in the L1B to support the MODIS consistent one-year data (re)-processing for the science community. MCST has provided quick on-orbit data analysis and developed all the required calibration LUTs for the L1B when the instrument configuration was switched from B-side electronics to A-side in July 2001. Solar diffuser stability monitor (SDSM) modeling has successfully identified existing problems in the system design parameters. The results will be used to improve SD degradation analysis for both the Terra and Aqua instruments. MCST has also successfully characterized the MODIS optics degradation and side-to-side differences in the scan mirror including angle of incidence (AOI) dependence features. Calibration workshops were organized and lead by MCST personnel during the MODIS Science Team meetings in January and December of 2001. For its contributions to the successful launch and early characterization of the Terra MODIS, MCST received a NASA 2001 Group Achievement Award.

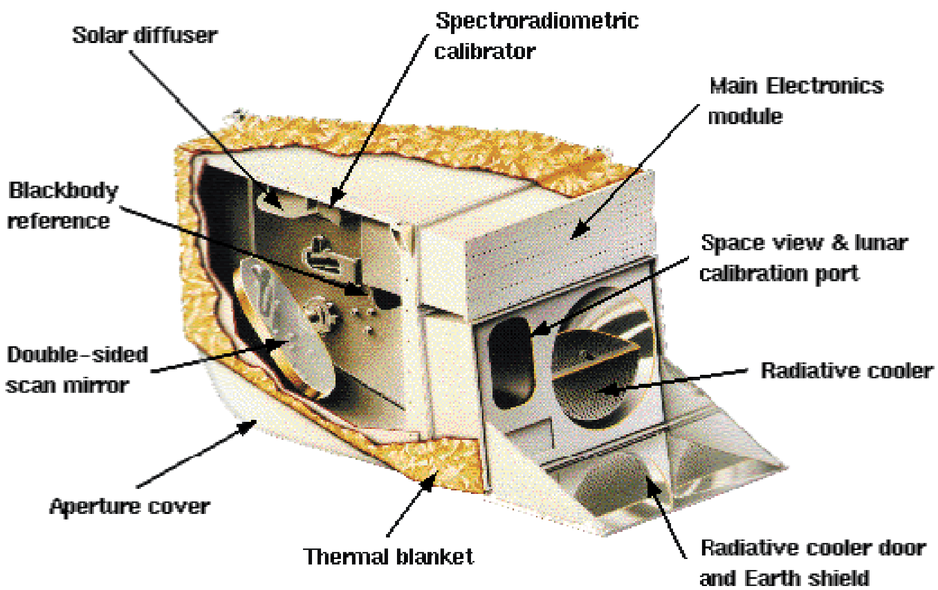

Figure 23. Moderate Resolution Imaging Spectroradiometer (MODIS).

Figure 24. Terra spacecraft with MODIS PFM on-board launched on December 18, 1999.

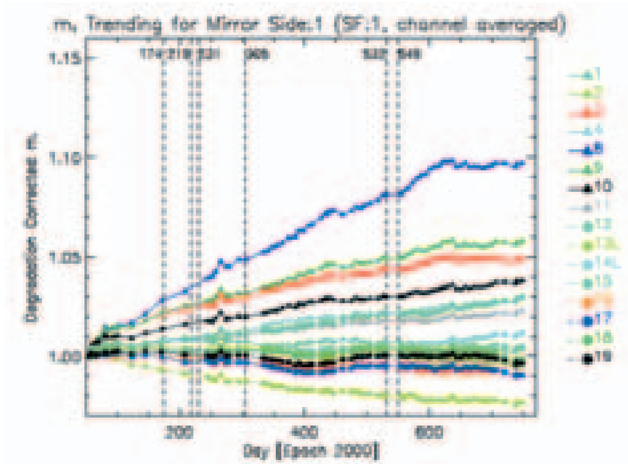

Figure 25. MODIS reflective solar bands reflectance scaling coefficients (m1) trending in 2000 and 2001 (SD degradation corrected, mirror side 1)

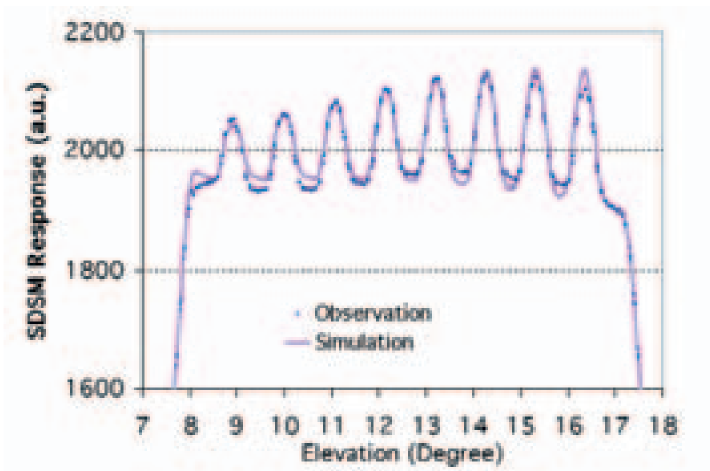

Figure 26. MODIS Solar Diffuser Stability Monitor (SDSM) simulation and on-orbit response comparison.

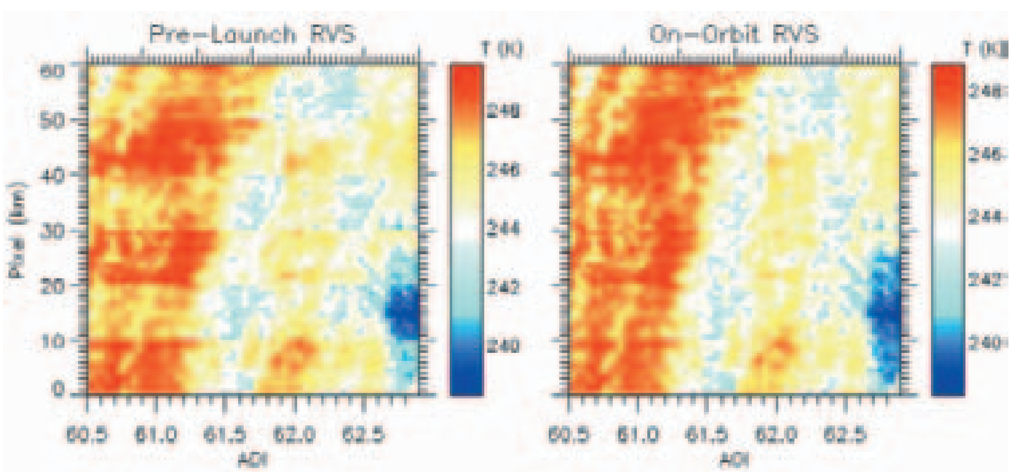

Figure 27. On-orbit RVS improvement (left image: using pre-launch RVS, right image: using on-orbit derived RVS, data from 2001197.1845)

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Laser Remote Sensing Branch

The mission of the Laser Remote Sensing Branch is to develop laser remote sensing techniques and instruments for scientific measurements of the Earth and planets. The Branch previously developed the ground-based Scanning Raman Lidar, the Shuttle Laser Altimeter (SLA) and the Mars Orbiter Laser Altimeter (MOLA) for the Mars Global Surveyor Mission. In ongoing work, we are developing the Geoscience Laser Altimeter System (GLAS) for the ICESat mission and the Mercury Laser Altimeter (MLA) for the Messenger Mission. Both of these projects are in partnership with Goddard's Applied Engineering and Technology Directorate (AETD). GLAS will precisely measure the height distribution of ice sheets, land topography, and backscatter from atmospheric clouds and aerosols, and MLA will measure the topography of Mercury. We are also developing an airborne surface imaging lidar and an airborne Raman Lidar. In research and development activities, we are developing new instruments which utilize tunable narrow linewidth lasers to remotely sense chlorophyll distributions and atmospheric trace gases such as CO_2.

For use in space, a lidar must be accurate, rugged, power efficient and operate largely autonomously. The space environment also imposes stringent requirements on the instrument's reliability and lifetime, mechanical and optical stability, thermal control, radiation tolerance and vacuum compatibility. The space lidar developed to date have used the direct detection technique with diode-pumped solid state laser transmitters, lightweight receiver telescopes, and solid-state detectors.

On the GSFC main campus the Branch utilizes 7 laboratories which are in Goddard's Earth System Sciences Building. Two laboratories are cleanrooms which are used to support instrument development for space flight projects. Several laboratories have upward or side-viewing optical ports for lidar testing. The Branch also has a mechanical laboratory, which is specialized for mechanical fabrication and assembly support needed for optical instruments. This lab contains two computerized milling machines, which are utilized for fabrication of specialized prototype parts for instruments.

The Branch also has a facility with several cleanrooms and laboratories at the Space Lidar Technology Center (SLTC) in College Park, MD. The Branch developed this facility in a cooperative agreement with the University of Maryland's A. James Clark School of Engineering. The purpose of the agreement provides a means for collaboration on lasers, opto-electronics, and material science related to instrumentation for space-based lidar. The SLTC facility was used to develop the GLAS flight lasers, and is equipped with two state-of-the-art cleanrooms, an ultra-clean vacuum chamber, and several support laboratories for developing lasers and electro-optic components.

Geoscience Laser Altimeter System (GLAS) for the ICESat Mission

The Geoscience Laser Altimeter System (GLAS) is a next generation space-lidar and is the primary science payload for NASA's ICESat Mission. The GLAS design combines a 10cm precision surface lidar with a sensitive dual wavelength cloud and aerosol lidar. GLAS will precisely measure the heights of the Earth's polar ice sheets, establish a grid of accurate height profiles of the Earth's land topography, and profile the vertical distribution of clouds and aerosols on a global scale. GLAS will be integrated onto a small spacecraft built by Ball Aerospace, and will be launched into a polar orbit with a 590-630km altitude at an inclination of 94^{o} as shown in Figure 28. ICESat is currently planned to launch in winter 2002/03 and GLAS is designed to operate continuously in space for a minimum of 3 years with a goal of 5 years.

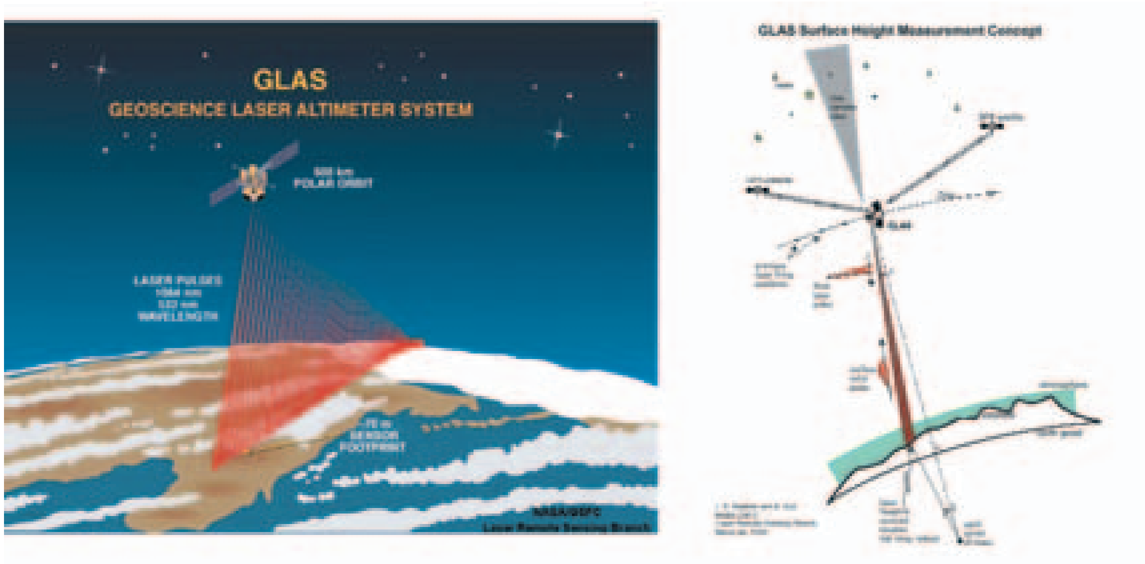

Figure 28. GLAS is the sole instrument of the ICESat mission. The instrument is being built in-house and tested at GSFC. Ball Aerospace is building the spacecraft at the Boulder, Colorado facility.

GLAS will measure the vertical distance from orbit to the Earth's surface with pulses from a Nd:YAG laser at a 40 Hz rate. The flight lasers have been designed and built by a 924 lead in-house GSFC team, one of three flight lasers is depicted in Figure 29.

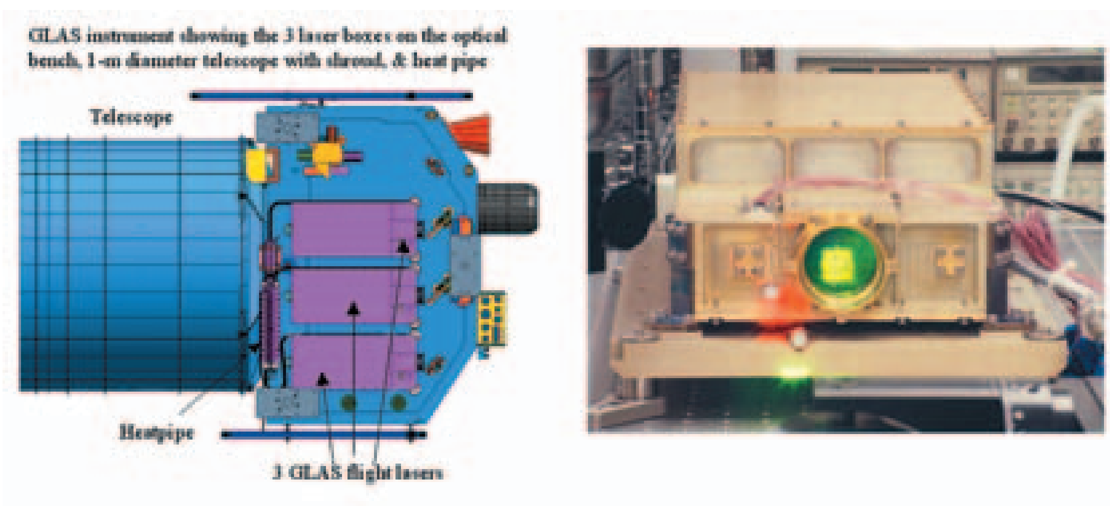

Figure 29. GLAS design showing location of all 3 lasers on instrument, and a flight laser on right.

Each GLAS laser pulse at 1064nm is used to produce a single range measurement to the surface. On the surface, the laser footprints have 66m diameter and ~ 170m center-center spacings. The GLAS receiver uses a 1m diameter telescope, shown in Figure 30, to collect the laser backscatter and a Si APD to detect the 1064nm echo pulses. The detector's output is sampled by a digital ranging receiver, which records each transmitted pulse and surface echo waveform with 1 nsec (15cm) resolution. Each echo pulse is digitized and is reported to ground with a record length from 200 to 544 samples, depending on the spacecraft's location. The GLAS location and epoch times are measured by a precision GPS receiver carried on the ICESat spacecraft. Initial processing of the echo waveforms within GLAS permits discrimination between cloud and surface echoes for selecting appropriate waveform samples. This selection is guided by an on-board DEM (digital elevation model) which is used to set the boundaries for the echo pulse search algorithm. Subsequent ground-based echo pulse analysis, along with GPS-based clock frequency estimates, permit final determination of the range to the surface, degree of pulse spreading, and vertical distribution of any vegetation illuminated by the laser.

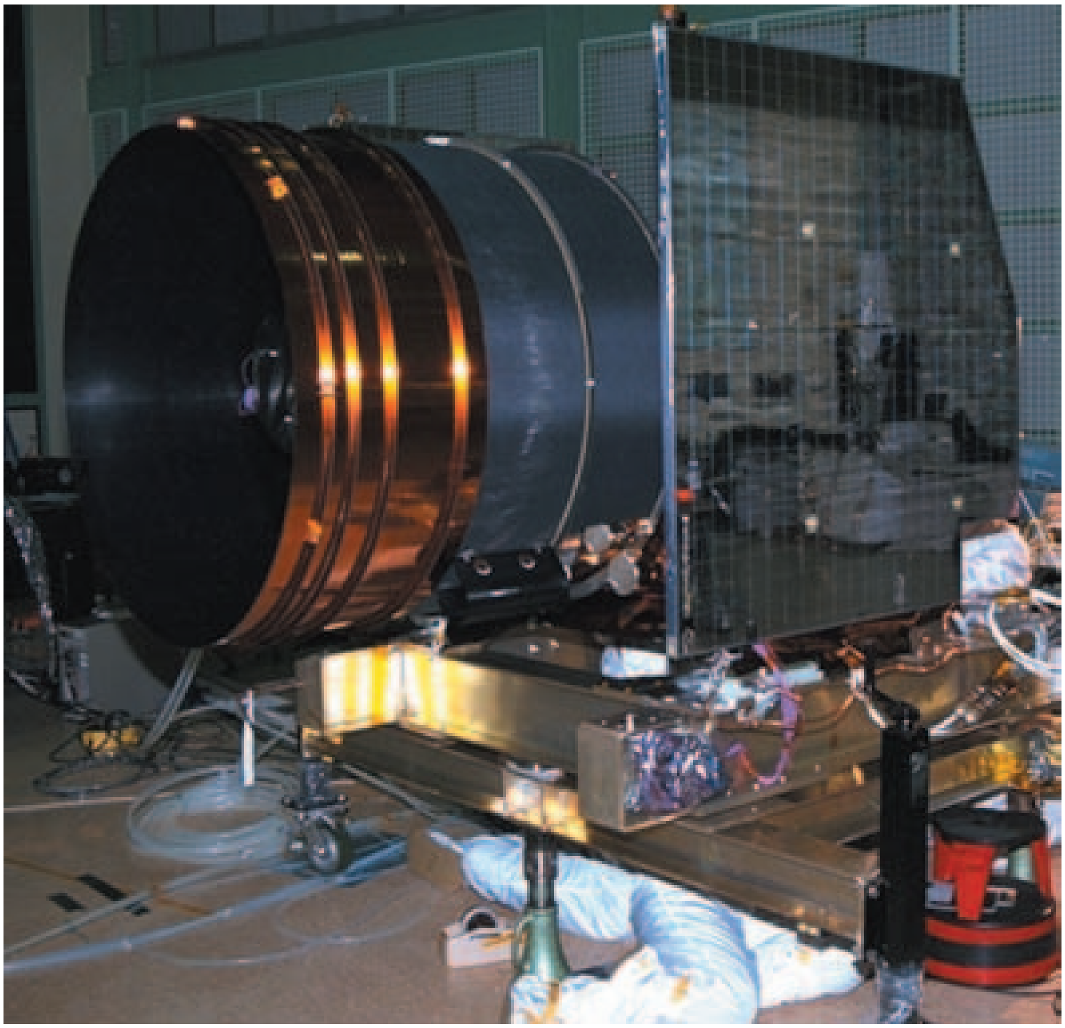

Figure 30. The GLAS instrument before environmental testing.

Accurate knowledge of the laser beam's pointing angle is needed to prevent height biases when measuring over tilted surfaces, such as near the boundaries of ice sheets. For surfaces with 2 deg. slopes, knowledge of pointing angle of the laser beam's centroid angle to better than 10μrad is needed. GLAS uses a stellar reference system (SRS) to measure the pointing angle of each laser firing relative to inertial space. The SRS, illustrated in Figure 31, uses a high precision star camera oriented toward local zenith and a gyroscope to determine the inertial orientation of the SRS optical bench. The far field pattern of each laser pulse is measured relative to the star camera with a laser reference system (LRS).

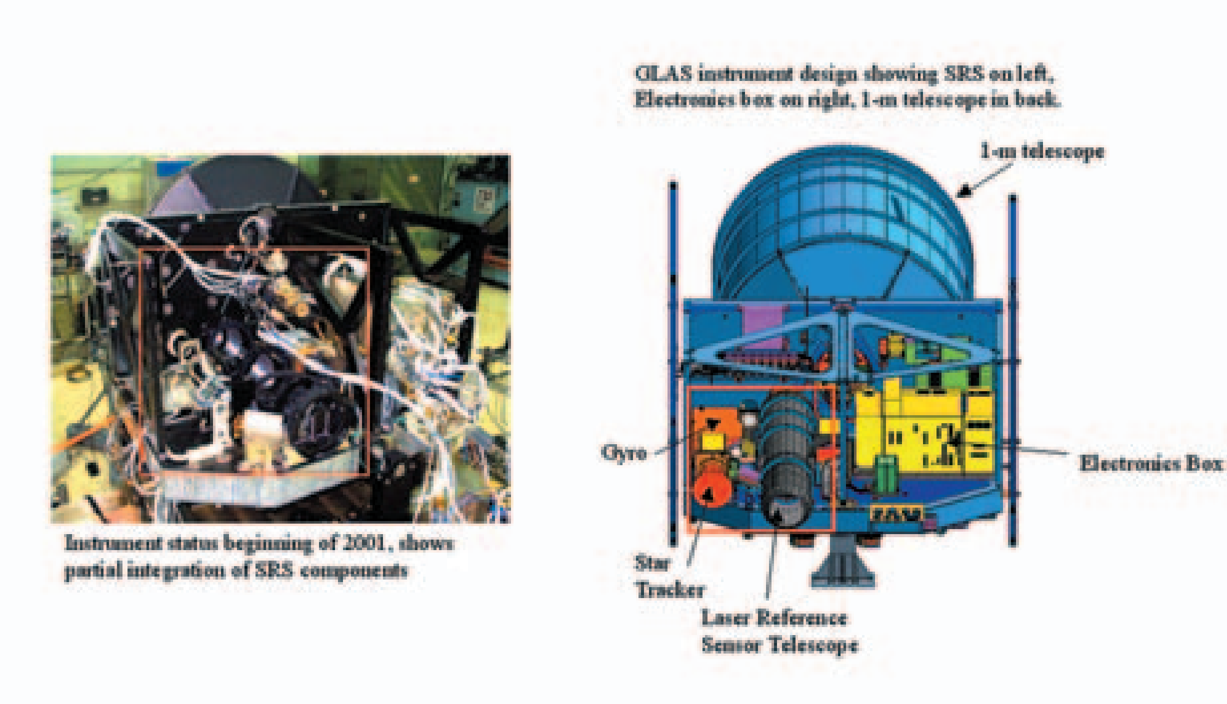

Figure 31. The zenith viewing side of GLAS, showing the GLAS SRS subsystem (shown in red box).

GLAS will also measure the vertical distributions of clouds and aerosols by recording the vertical profiles of laser pulse backscatter at both 1064nm and 532nm. The 1064nm measurements use the Si APD detector and will be used to measure the height and echo pulse shape from thicker clouds. The lidar receiver at 532nm uses a narrow bandwidth etalon filter and highly sensitive photon counting detectors. The 532nm backscatter profiles will be used to measure the vertical extent of thinner clouds and the atmospheric boundary layer. The GLAS instrument component development is complete and the instrument is undergoing final testing and qualification at NASA's Goddard Space Flight Center.

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GLAS Laser Transmitter

GLAS carries three identical laser transmitters. The GLAS laser design was developed and manufactured at Goddard, and represents a new generation of lasers for space remote sensing. The laser transmitter emits 6nsec wide laser pulses at two different wavelengths simultaneously at a 40 Hz rate. The laser pulse energies are 75mJ @ 1064nm and 35mJ at 532nm. The laser far field pattern is nominally gaussian and has a beam divergence of 110µrad. The wall plug efficiency of the lasers is 4.5%. The laser components are radiation tolerant and the laser cavities operate in vacuum after launch. Environmental testing has shown the lasers are rugged and capable of long term operation in vacuum over temperature ranges expected by the instrument. The expected lifetime per laser is > 2 Billion shots, which should permit a GLAS instrument lifetime in excess of 3 years.

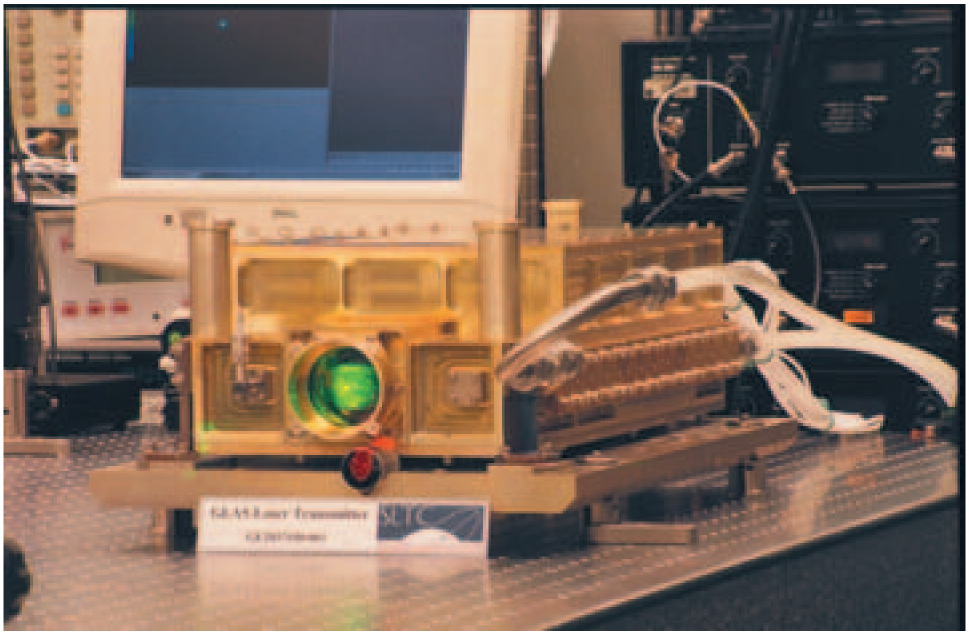

Figure 32. A side viewing of GLAS Laser SN1 during testing at the SLTC.

The GLAS laser configuration is a master-oscillator, power-amplifier (MOPA) design which incorporates a Lithium Triborate doubler for converting some of the fundamental 1064nm pulse energy to 532nm. The laser is all solid state and all laser stages are pumped with quasi-CW 100W laser diode bars. Figure 32 shows one of the 3 flight lasers fabricated at the SLTC (Space Lidar Technology Center) located at the University of Maryland in College Park, MD.

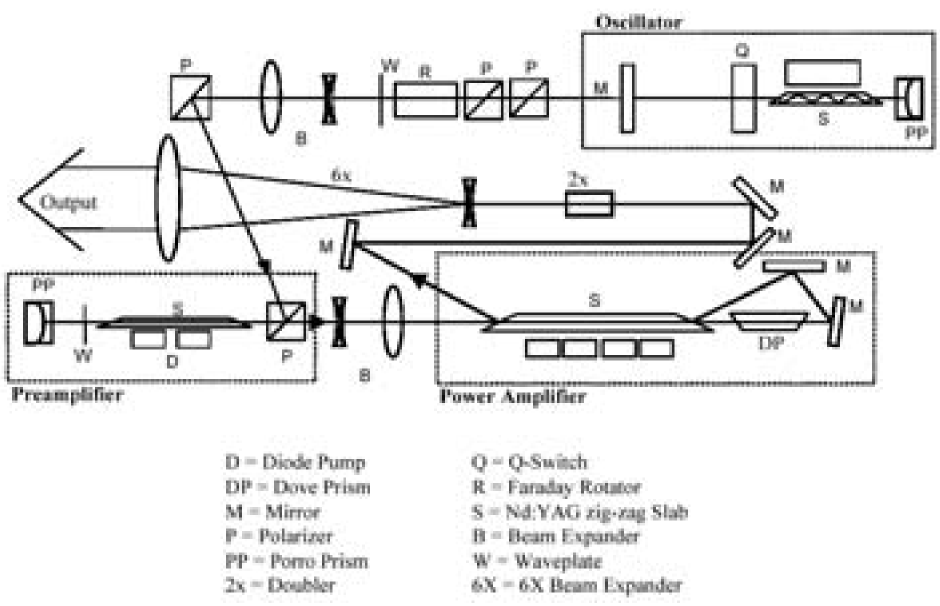

Figure 33. Schematic of GLAS laser optical layout.

A schematic of the optical layout within the laser housing is shown in Figure 33. The oscillator, is passively q-switched and is pumped by two diode-bars. It generates 5nsec wide laser pulses at 1064nm with 2mJ energy/pulse. The pulses occur at a 40 Hz rate and have a nearly diffraction limited spatial profile. The output pulses from the oscillator are expanded by a 2x telescope, and amplified by a double-pass preamplifier stage. This stage is pumped by 8 diode bars and its output laser pulses have 15mJ. After another 2x expansion, the beam enters a power amplifier, which is pumped by 44 diode bars. This stage utilizes a polarization coupled double pass zig-zag slab with a porro-prism for beam symmetrization. The pulses are amplified to 110mJ after a double pass through the amplifier. The peak laser fluence in the final amplifier is 4J/cm2. The beam from the amplifier is then directed to a Lithium Triborate frequency doubler, which converts 30% of the energy to 532nm. The two-color output beam then passes through an achromatic, 6 power beam expander, and then exits the laser box through a window and pair of risley prisms.

To accommodate the needed lifetime, all pump diode bars and optical coatings were used at less than their rated maximums. The oscillator diodes are derated to 65W/bar (85A) and the amplifier diodes are derated to 85W/bar (100A). The laser contains its own special power supply, and operates from 28V spacecraft power. The laser is all conductively cooled, with a heat pipe thermal interface at the side-wall of the laser housing. The lasers draw off 110W @ 30V input. Before delivery, each flight laser underwent a 3-axis qualification vibration test, and underwent an extensive thermal vacuum test. This included 2 cycles at survival temperatures (0° to 40° C), 3 cycles at operational temperatures (10° to 35°C), and two additional cycles with the laser interior pressured. All flight lasers accumulated over 50 million shots each before delivery to GLAS for integration.

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GLAS Stellar Reference System (SRS)

In order to meet the altimetry accuracy requirement, GLAS must accurately measure the pointing angle of every laser pulse. The error of the altimetry measurement of GLAS includes the accuracy of the dual frequency GPS solution for spacecraft position, timing uncertainty in the ranging measurement, and pointing knowledge of the laser. The GLAS stellar reference system will measure the pointing of every laser pulse with respect to inertial coordinates with an accuracy of 7 µrad. This is the first time that a spaceborne laser system has directly measured the pointing angle of its laser beam, and results in a highly accurate altimetry measurement.

The SRS is comprised of two commercial star trackers, one having a very narrow field of view for increased accuracy, a HRG, and angle preserving beam steering optics. Data from these sensors is time-tagged and post-processed on the ground via Kalman filtering for pointing knowledge determination.

The SRS provides calibrated knowledge of the laser pointing direction with respect to the instrument optical bench. Its measurements are combined with the Precision Orbit Determination (POD) results and the measured round trip travel time for the laser pulse. The results permit determination of both the laser spot location on the Earth surface and the surface elevation with respect to the Terrestrial Reference Frame (TRF). The attitude determination is a necessary process in the laser pointing determination, where attitude is practically defined as the angular orientation of the optical bench with respect to the Celestial Reference Frame (CRF). The GLAS attitude determination system (ADS) includes the HD-1003 star tracker and a Litton HRG unit. The star tracker and gyros are mounted on a rigid optical bench with the other SRS components. In summary, simulation results show that the GLAS attitude can be determined with an accuracy of 1.4 µrad (1σ) in each of the roll and pitch axis using a Kalman filter.

Conceptually, the pointing angle of the GLAS laser beam could be determined by coupling the laser beam directly into a star camera. Unfortunately this is not feasible with current star tracker technology for the needed pulse rates and angular resolutions. Thus, an approach using a separate sensor to measure the pointing of the sampled laser beam at 40 Hz was chosen. The overall approach for the stellar reference system is shown in Figure 34. The ADS measures the pointing of the instrument platform with respect to the star field while the laser reference sensor (LRS) samples the laser beam at 10 Hz and measures its alignment with respect to the components of the ADS. The Laser Profiling Array (LPA) measures the spatial profile of the laser beam at 40 Hz.

In the SRS a small fraction of the GLAS laser beam is folded into the laser reference sensor field of view (FOV) with two lateral transfer retroreflectors (LTR's). LTR's have the same characteristics as retro-reflectors; they preserve the parallelism between the input and output beams as long as the alignment integrity between the three faces are maintained. The first LTR encountered by the outgoing laser beam is constructed with a semi-transparent fused silica facet and two other Zerodur facets which form the dihedral of the LTR. The fused silica output facet is anti-reflective (AR) coated while the other two Zerodur facets have highly reflective coatings. The next LTR, constructed entirely of highly reflective coated Zerodur, relays the laser beam and a fiducial beam into the laser reference telescope where they are imaged for each laser shot fired.

The LRS consists of a (8.5 x 8.5mrad) FOV camera operating at 10 Hz frame rate. The camera includes a newtonian telescope, a charge coupled device (CCD) array, and ancillary electronics for imaging and computing the centroid locations of the GLAS laser beam and other reference images. Also coupled into the telescope is the collimated reference source (CRS) beam which is rigidly mounted to the star tracker housing for the purpose of checking the star tracker alignment.

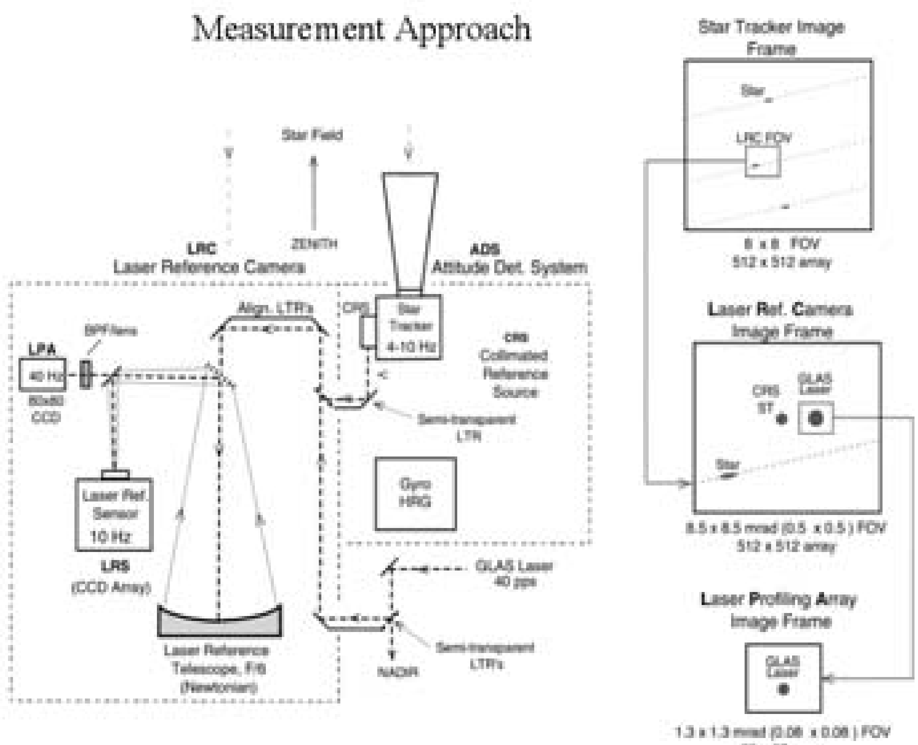

Figure 34. GLAS Stellar Reference System conceptual approach. The GLAS laser beam is coupled into the LRS along with the collimated reference source from the ADS. All optical beams are introduced concentrically through the semi-transparent diagonal mirror of the telescope.

The alignment and stability between the CRS and the star tracker CCD array will influence how well the pointing of the GLAS laser beam can be determined, these error components are accounted for in the LRS error budget. The LRS is also able to image stars every few minutes on average which will enable a boresight check between the LRS and the larger FOV (8° x 8°) star camera. An aperture of about 120 cm^2 total area is available for collecting star light in the laser reference telescope (LRT). The LPA is an 80 x 80 pixel array with the same FOV per pixel as the LRS and images each laser shot fired. The relative movement between the far field pattern of the GLAS laser beam, reference source from the star tracker, and an occasional star will be determined. This data combined with the processed ADS data yields the pointing of the laser beam in inertial space.

The error budget allotment of the SRS can be separated into two sections, a laser reference system and attitude determination system (ADS). The laser reference system is comprised of the camera centroid resolution (for lasers and star images), LTR stabilities, telescope distortion and star tracker boresight. The total RSS error of this section is 5.4 µrad (1σ). The ADS error component, totaling 2.4 µrad, is derived by Kalman filtering the performance specifications of the Litton HRG gyro with those of the HD-1003 star tracker. The laser reference system is the core instrument of the SRS, it combines the laser reference camera (CCD array plus telescope) with coupling optics and reference sources. All components of the LRS system have already been tested, with measured performance used in the error budget. The LRS and the ADS RSS (1σ) error total is 5.72 µrad which is less than the 7 µrad requirement.

In 2001 the SRS components have been environmentally tested and integrated to the flight bench. The subsystem has been calibrated with bench checkout equipment, designed and developed by the same team. The SRS meets the performance specification of determining the pointing angle of the GLAS laser beam to 7 µrad.

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Mercury Laser Altimeter (MLA)

MLA is a space-based lidar and is one of the primary scientific instruments aboard the NASA MESSENGER mission. The MErcury Surface, Space Environment, GEochemistry and Ranging, is a planetary mission to Mercury which is part of the NASA Discovery program. The spacecraft will be launched in March 2004, and will arrive at Mercury on April 2009. MESSENGER will orbit the planet and perform scientific measurements for a period of four Mercury years, which is about 360 Earth days.

The measurement objectives of MLA are to determine the shape of the planet and the amount of libration in the planet's rotation; provide a high precision topographical map of the Mercury northern hemisphere; and provide a measurement of the bi-directional reflectivity of the Mercury surface at 1064 nm wavelength. The MLA measurements will be used to answer questions about the Mercury planet, such as its formation and geological history, the structure and state of the core and surface material composition. The MESSENGER principle investigator is Sean Solomon of Carnegie Institution of Washington. The spacecraft is built and managed by The Johns Hopkins University Applied Physics Lab (APL). The MLA instrument principal investigator is David E. Smith of Goddard's Laboratory for Terrestrial Physics.

The MLA laser transmitter is a diode-pumped Nd:YAG laser, which produces ~ 20mJ/pulse at 1064nm at a 8 Hz rate. The receiver consists of four refractive telescopes, a silicon avalanche photodiode, timing electronics, and a microprocessor. The total instrument mass is under 8kg and the average power consumption is under 20 Watts. The maximum ranging capability is predicted to be 800km to 1200km, depending on the time of the year, and the accuracy is estimated to be better than 1 meter at low (200km) altitude, including the effect of the instrument noise floor and spacecraft pointing uncertainty. Among the challenges of the MLA development are the severe thermal environment around Mercury, highly elliptical spacecraft orbit, the mass and power constraints, and the tight schedule and budget.

The MLA instrument is being designed and constructed by a Goddard Instrument Team, which includes several key members from the Laser Remote Sensing Branch. The MLA design is based on heritage from the Mars Orbiter Laser Altimeter (MOLA) and the Geoscience Laser Altimeter System (GLAS), both of which were led by the Laser Remote Sensing Branch. The MLA instrument preliminary design review was held in April, 2001, and the critical design review was held in February 2002. The flight instrument is scheduled for delivery to the spacecraft for integration and testing in spring 2003.

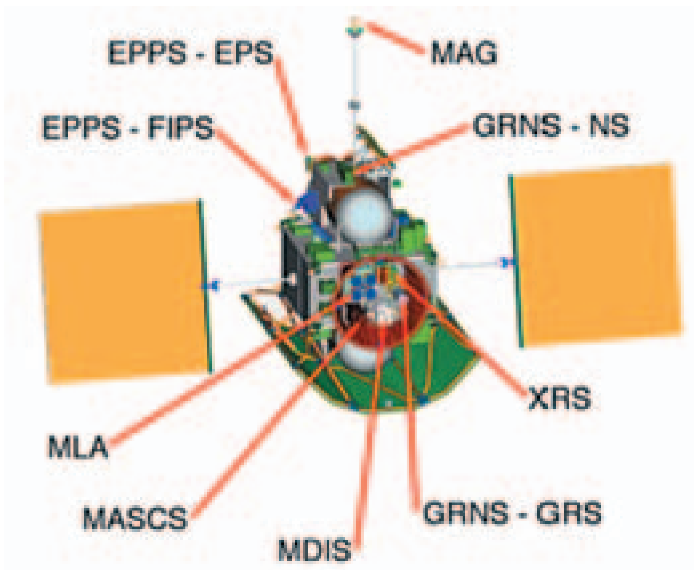

Figure 35. MESSENGER spacecraft – view from rocket attachment side.

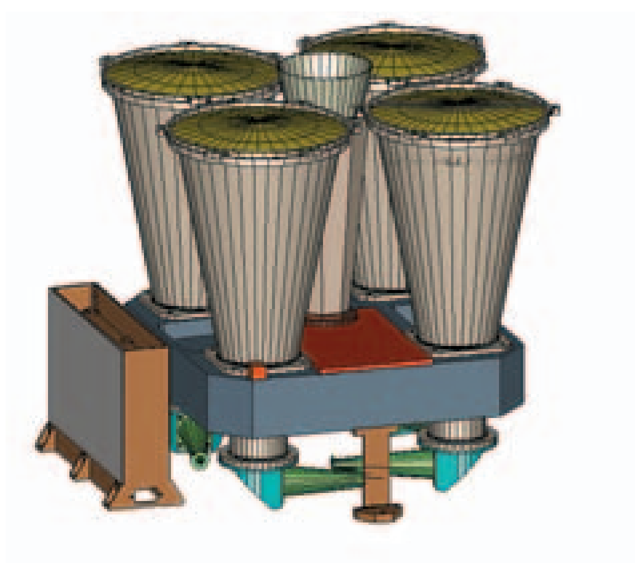

Figure 36. MLA Instrument – side view.

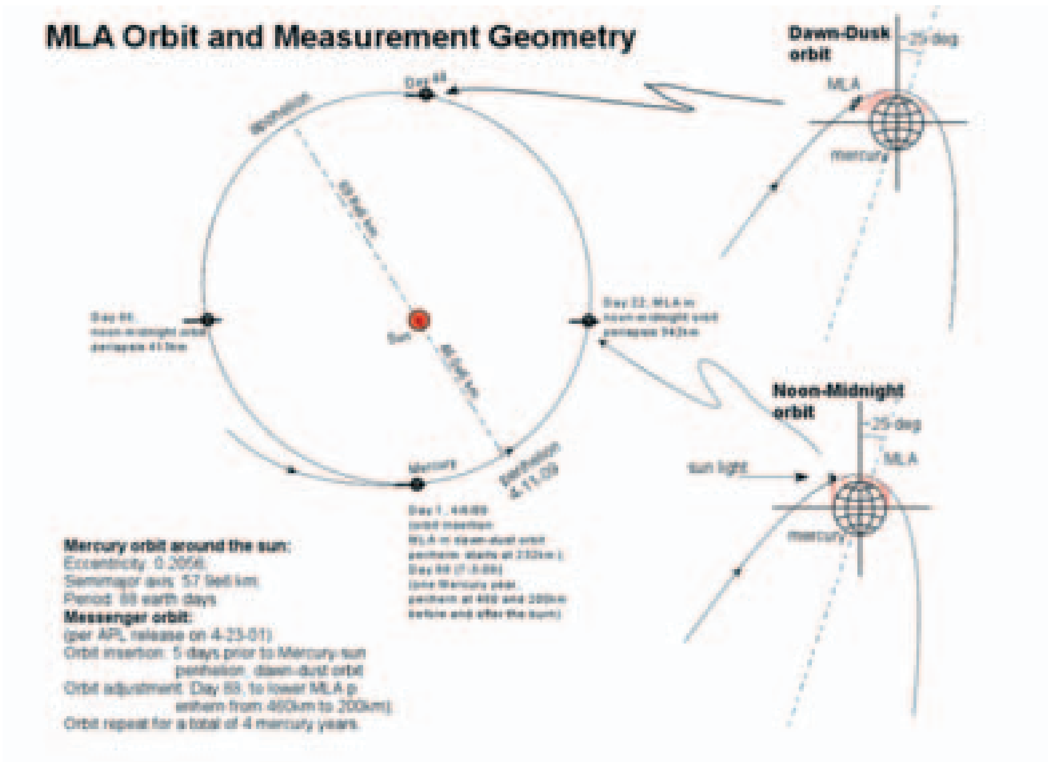

Figure 37. MLA Orbit and Measurement Geometry.

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Mars Orbiter Laser Altimeter (MOLA)

Background

MOLA is one of the primary instruments on the Mars Global Surveyor. The MOLA instrument, shown in Figure 38, was designed and built by a GSFC instrument team lead by the Laser Remote Sensing Branch. The laser was designed and built by the McDonnell Douglas Corporation. As of 6/30/01 MOLA had been in space for 1696 days and had undergone 216 power-on/off cycles. The laser had fired 671 million times in space and MOLA had made ~640 million measurements of the Mars surface and atmosphere.

MOLA has been extremely successful and made more than ten times the number of laser measurements than all previous space lidar instruments combined. The MOLA instrument performance and lifetime surpassed all goals of the MOLA investigation.

Radiometry Measurements of Mars at 1064nm using the Mars Orbiter Laser Altimeter

The clock oscillator in MOLA stopped in June 2001, which precluded any additional ranging measurements since then. A mathematical model and receiver calibration have been developed to use the measurements by the MOLA on board the Mars Global Surveyor (MGS) to provide a radiometric measurement of Mars in addition to its topographic measurement.

MOLA was designed primarily to measure Mars topography, surface roughness, and the bidirectional reflectance to the laser beam. To achieve the highest sensitivity, the receiver detection threshold is dynamically adjusted to be as low as possible while keeping a predetermined false alarm rate. The average false alarm rate is monitored in real time on board MOLA via a noise counter, whose output is fed to the threshold control loop. The false alarm rate at a given threshold is a function of the detector output noise, which is the sum of the photodetector shot noise due to the background light seen by the detector and the dark noise. A mathematical model has been developed that can be used to numerically solve for the optical background power given the MOLA threshold setting and the average noise count. The radiance of Mars can then be determined by dividing the optical power by the solid angle subtended by the MOLA receiver, the receiver optical bandwidth, and the Mars surface area within the receiver field of view. The phase angle which is the sun-Mars-MOLA angle is available from the MGS database. MOLA also measures simultaneously the bidirectional reflectance of Mars via its 1064nm laser beam at nadir with nearly zero phase angles.

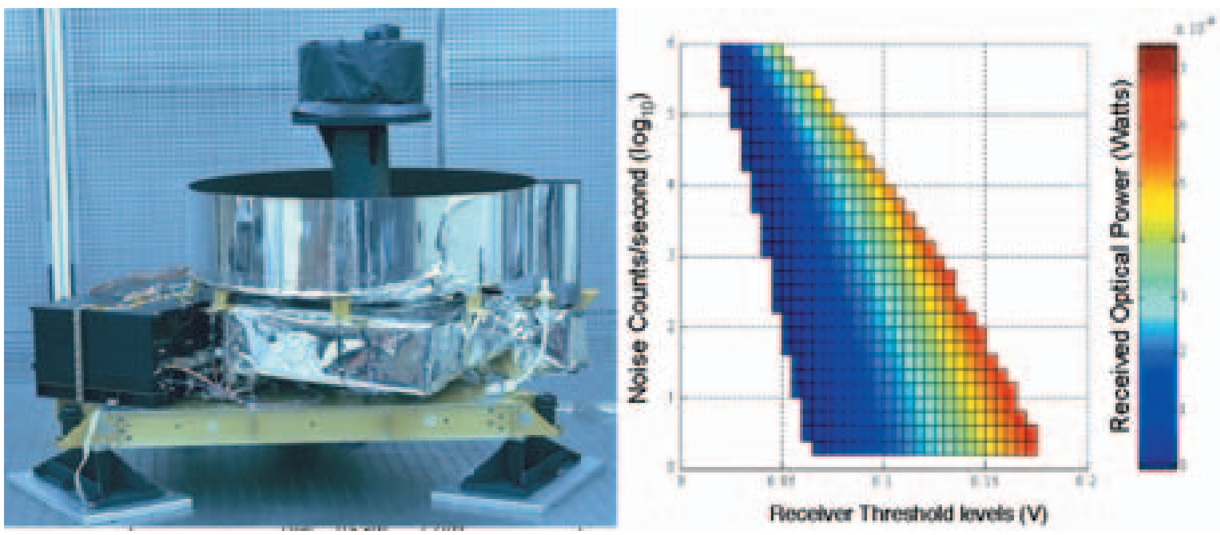

Figure 38. The Mars Orbiter Laser Altimeter (MOLA). The laser is situated beneath the 0.5-m telescope, the radiometer response function is shown on the right.

The optical bandwidth of the MOLA receiver is 2nm full width at half maximum (FWHM) and centered at 1064nm. The receiver field of view is 0.85mrad FWHM. The nominal spacecraft altitude is 400km and the ground track speed is about 3km/s. Under normal operation, the noise counters are read and the threshold levels are updated at 1Hz. The receiver sensitivity is limited by the detector dark noise to about 0.1nW, which corresponds to <2% the maximum radiance during daytime from the brightest area on Mars.

The results from the mathematical model agree well with the pre-launch measurements at several calibrated optical power levels. The radiance of sunlit Mars estimated with this technique correlates well with the measurement from the MGS Thermal Emission Spectrometer (TES) and the Hubble Space Telescope at similar wavelength. According to the Citation Index, the MOLA measurements and instrument have been cited in 55 peer reviewed articles through December 2001.

Project Scientists: Xiaoli Sun, James B. Abshire, Gregory A. Neumann, and Maria T. Zuber

References

J. B. Abshire, X. Sun, and R. S. Afzal, 'Mars Orbital Laser Altimeter: receiver model and performance analysis,' Applied Optics, Vol. 39, No. 15, pp. 2449-2460, May 2000.

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Water Vapor Raman Lidar

Background

Water vapor is perhaps the most important of the atmospheric state variables and strongly influences atmospheric radiation and dynamics. It is a stronger greenhouse gas than carbon dioxide and any global warming scenario must accurately predict the influence of CO_2-induced temperature changes on atmospheric water vapor content and clouds (condensed vapor). Water vapor in the upper troposphere is the main determinant of the Earth's ability to radiate heat to space. Small changes in water vapor amounts in the upper troposphere make large changes in the net radiation budget of the planet.

In the area of dynamics, the spatial distribution of water vapor determines atmospheric stability and the likelihood of convection initiation. The great challenge of measuring water vapor accurately is that, as opposed to the other state variables, water vapor displays very large spatial and temporal variability. An understanding of the mechanics of storm formation must take account of this high variability and to date only lidar has demonstrated the ability to capture this variability at high resolution throughout the atmospheric boundary layer.

A large multi-national field campaign called IHOP (the International Water Vapor Project) is being sponsored by various agencies of the U.S. government and foreign governments. It will occur in the summer of 2002 in the central US. It's main goal is to improve the understanding of how the spatial distribution of water vapor influences the onset of convection and the amount of rainfall that is produced by convective systems. The NASA/GSFC Scanning Raman Lidar (SRL) has been identified, since the beginning of the planning of this field campaign, as a crucial instrument for IHOP and recently has obtained funding from NASA HQ to participate in this experiment.

The SRL has recently demonstrated unprecedented high resolution measurements of water vapor during the night. During the Water Vapor Intensive Operations Period 2000 experiment, sponsored by the Department of Energy at its northern Oklahoma test site, the SRL was used to acquire water vapor mixing ratio data with 7.5 m spatial resolution and 10 second temporal resolution with less than 10% random error up to an altitude of 5km. These are the highest resolution measurements of water vapor ever acquired, unmatched by any other technology. Such measurements directly address the central need of IHOP to quantify water vapor variability at the highest resolution possible to better understand the mechanics of storm formation.

During fiscal year 2001, the Raman lidar group was involved in several funded activities. Brief descriptions of those activities, their periods of performance and accomplishments follow.

Raman Airborne Spectroscopic Lidar (RASL)

RASL is an airborne Raman lidar that will offer a broader suite of atmospheric measurements than any existing airborne lidar. It will measure water vapor, aerosol extinction/backscatter/depolarization, cloud liquid water, and cirrus cloud particle radius. RASL is based on a 61cm diameter telescope, with a 17.5W Nd:YAG laser, photomultiplier tubes and combined analog and photon counting data acquisition.

In 2001, a Continuum Nd:YAG laser, the data acquisition system and all detection optics have been received and tested. The schedule is for ground-based, laboratory demonstration of RASL to begin in March 2002.

Scanning Raman Lidar (SRL) participation in WVIOP2000/AFWEX

The Department of Energy's (DOE) Atmospheric Radiation Measurements (ARM) program hosted two field campaigns focused on comparison of water vapor measurement technology. The Water Vapor IOP2000 (Sept – October, 2000) campaign was concerned with assessing accuracy of tropospheric water vapor measurement instrumentation, while the AFWEX (Nov - Dec 2000) campaign was concerned with upper tropospheric measurements. The SRL was funded for participation in both of these campaigns and was used to demonstrate the best daytime Raman lidar measurements of water vapor ever acquired. It also demonstrated improved upper tropospheric water vapor measurements and identified a lower atmospheric bias in the DOE Raman water vapor lidar (CARL). The validity of CARL cirrus cloud optical depth measurements were also established.

Micropulse lidar (MPL) aerosol validation measurements

The SRL also supported comparison measurements with the GSFC MPL during periods of heavy aerosol loading. The MPL algorithm for determining aerosol extinction from backscatter data was compared with the direct retrievals of extinction using the Raman measurements of nitrogen provided by the SRL.

Preliminary comparisons indicate that for atmospheric conditions with single aerosol layers the measurements agree well. However, under the presence of multiple extinguishing layers significant differences have been found. Work continues on using these comparison measurements to fine-tune the MPL algorithm under difficult conditions such as multiple layers.

AQUA validation activities

The Raman lidar group has been funded through the EOS validation program for three years of research aimed toward validation of the AIRS sensor on the AQUA spacecraft.

During the AIRS initial checkout, which are to occur in June – August 2002, Raman lidar measurements of upper tropospheric water vapor will be acquired during AIRS overpasses. During years two and three Raman lidar measurements during the presence of thin cirrus will be used to assess the influence of thin cirrus clouds on AIRS measurements of water vapor.

SuomiINet International GPS Network participation

SuomiNet is an international network of GPS stations for acquiring atmospheric and geodetic measurements. Our SuomiNet site, referred to as SA02, was established in the Raman lidar laboratory on August 15, 2001. This was the 6th SuomiNet site to become operational. It will be used for continuous monitoring of atmospheric precipitable water, temperature, pressure and relative humidity. These data will be used for satellite validation activities as well as for comparison with Raman lidar measurements of water vapor.

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Laser Vegetation Imaging Sensor (LVIS)

Lidar measurements of vegetated land provide unprecedented views of the vertical and horizontal structure of the tree canopies and topography beneath. Lidar provides a unique view of the actual physical surfaces of the ground and canopy and permits important biophysical parameters such as biomass to be estimated with substantially improved accuracy. By utilizing medium to large diameter laser footprints and recording the entire time history of interaction between a short pulse of laser light and the surface of the Earth, the vertical structure of vegetation including canopy height, a profile of vegetation material down through the canopy, and sub-canopy topography can be measured. The Laser Vegetation Imaging Sensor (LVIS) was designed to produce direct measurements of vegetation height and topography, as well as produce estimates of above-ground biomass for the mapped regions. These data act as a link between small area ground sites and large area mapping by satellite sensors allowing calibration of satellite sensors to be linked to small study areas.

LVIS is a scanning airborne laser altimeter (Figure 39) which uses a 2km wide swath and full echo-waveform processing. It was developed at GSFC and is optimized for measuring topography (including sub-canopy) and vegetation height and vertical structure. LVIS measurements have been used to produce some of the best estimates of above-ground biomass in densely forested regions (Figure 40). LVIS has been selected to map ~20,000km^2 in the Amazon. The flight mission is planned for June-August of 2003.

The LVIS instrument was recently redesigned. The updated instrument design is complete, the laser transmitter has been upgraded, and work is well underway to build the new LVIS telescope and upgrade the data system. This upgraded data system significantly expands the instruments capabilities and allows the utilization of multiple processors, communication with ancillary data devices and remote computers via ethernet in real-time, redundant data storage in real-time, and increasing the laser pulse-rate to 5,000 Hz. Local science experiments will be performed in Maryland and Pennsylvania in the summer of 2002 to test the upgraded LVIS before deployment in Brazil.

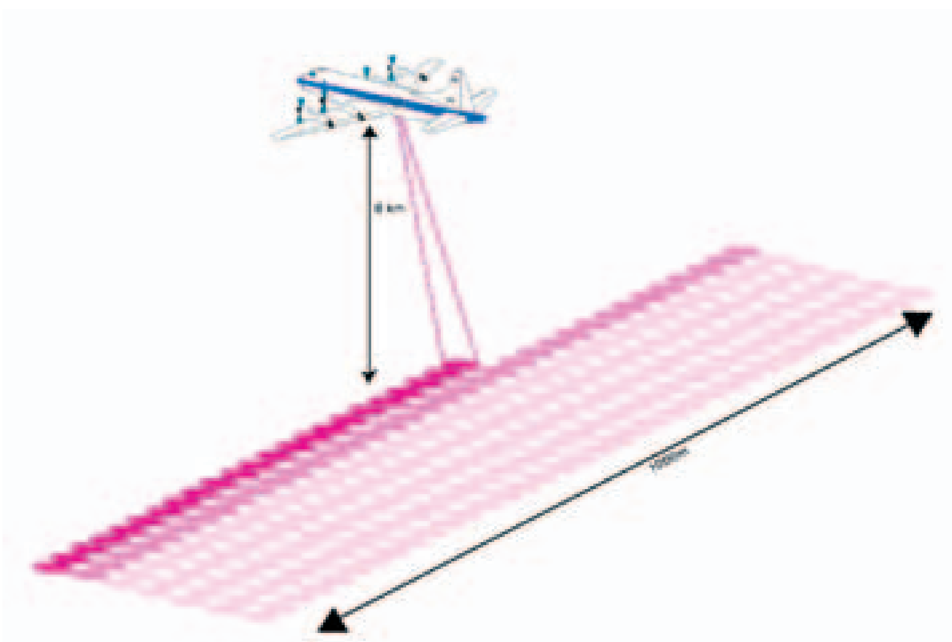

Figure 39.

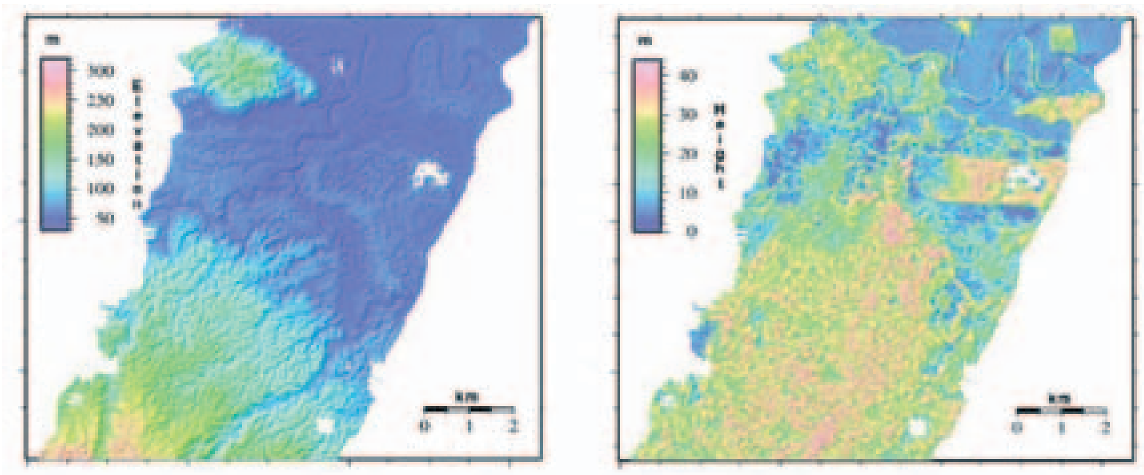

Figure 40.

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Mixed Layer Lidar Remote sensing of the Ocean's Boundary Layer

Background

The rapid increases in atmospheric CO_2 appear to be causing warming of the global climate. The extent of warming is largely influenced by corresponding changes in the average temperature of the oceans. In a recent issue of Science magazine, a NOAA research team reported the first evidence of the expected increase in ocean temperature, based on 50 years of field measurements. Dr. James Hansen of the NASA Goddard Institute for Space Sciences (GISS) stated that "The rate of heat storage in the ocean is the single most important number that we need to check our understanding of decadal climate change" (Washington Post, 24 March, 2000). Remote sensing measurements are critical for monitoring variability in sea surface temperatures, but global changes in stored heat within the ocean surface are a product of both surface temperature and the depth of the ocean mixed layer. To date there has been little work on assessing remote sensing approaches to globally measure the ocean's mixed layer depth.

Thermal stratification of the surface ocean causes heterogenous distributions of scattering particles through the water column that should be resolvable with an airborne lidar. Absorption of solar radiation warms the upper layer of the ocean and decreases its density, thereby impeding exchange with the colder, denser water below. Physical forcing factors, such as wind stress, internal waves, and tidal mixing, provide the energy to homogenize surface water temperatures to a limited depth (i.e., the mixed layer). The interplay between light absorption and physical mixing results in a predictable depth-dependent temperature distribution: a uniform warmer-temperature surface layer, followed by a rapid temperature gradient starting at a depth ranging from 10 to >100m (the 'thermocline'), and a deep cold bottom layer. Density differences corresponding to these distinct layers provide the key to remotely detecting the depth of the thermocline and, thus, the depth of the mixed layer.

Biological processes in the mixed layer produce a flux of particles that slowly sink. Density changes at the thermocline cause sinking rates to decrease and result in an accumulation of particles. As observed by Dr. Ronald Zaneveld and colleagues at Oregon State University (OSU group), particle accumulation at the thermocline results in a local optical scattering maximum in most ocean regions. Modeling studies by the OSU group indicate that the depth of this scattering layer can potentially be evaluated from space by using lidar measurements.

There are a number of issues to assess in determining the feasibility of a satellite-based Mixed Layer Lidar (MLL). They include laser power, receiver photon collection techniques and telescope area and sensor dynamic range. As an example, the subsurface scattered signal can be attenuated from the ocean surface echo by as much as four orders of magnitude. Key to resolving most of the unknowns is determining the strength and characteristics of the laser signal scattered from the subsurface layers. The next step in assessing the feasibility of a space-based MLL mission is to conduct 'proof-of-concept' field measurements first with a ship-based lidar.

Ship-based Mixed Lidar Layer

A ship-based mixed layer lidar will be used to help quantify the surface interaction of the laser pulse reflecting and refracting at the air/water boundary. The ocean surface wave characteristics span a wide spectrum, from small amplitude, high frequency capillary waves to low frequency swells. These surface conditions will determine how much laser energy is transmitted into the water and the path that this energy travels before scattering. To be useful from space, these effects must be quantified and algorithms developed to remove them from the backscatter data. Two approaches will be used to gain an understanding of these surface interactions; 1) An optical model of the ocean surface will be developed and ray-tracing will be performed to try and bound the problems of reflection, scattering, and refraction (lensing) at the surface; 2) A calibrated breadboard lidar instrument will be tested at the David Taylor Modeling Basin in Carderock MD and compared to the model developed in 1). Complete control over the induced wave spectrum at the Modeling Basin will enable a thorough evaluation of the model.

A conceptual design for the Mixed Layer Lidar was developed based on information obtained from a final report from Zaneveld, et al and acquired from a visit to the Naval Air Warfare Center (NAWC), in Patuxent, MD in February 2001. The prototype instrument and approach is shown in Figure 41. However, these instruments were not calibrated and there was no interest in measuring, monitoring, or correcting for effects at the water/air interface, e.g. Fresnel reflection and lensing or refractive effects due to concave/covex nature of waves and swells.

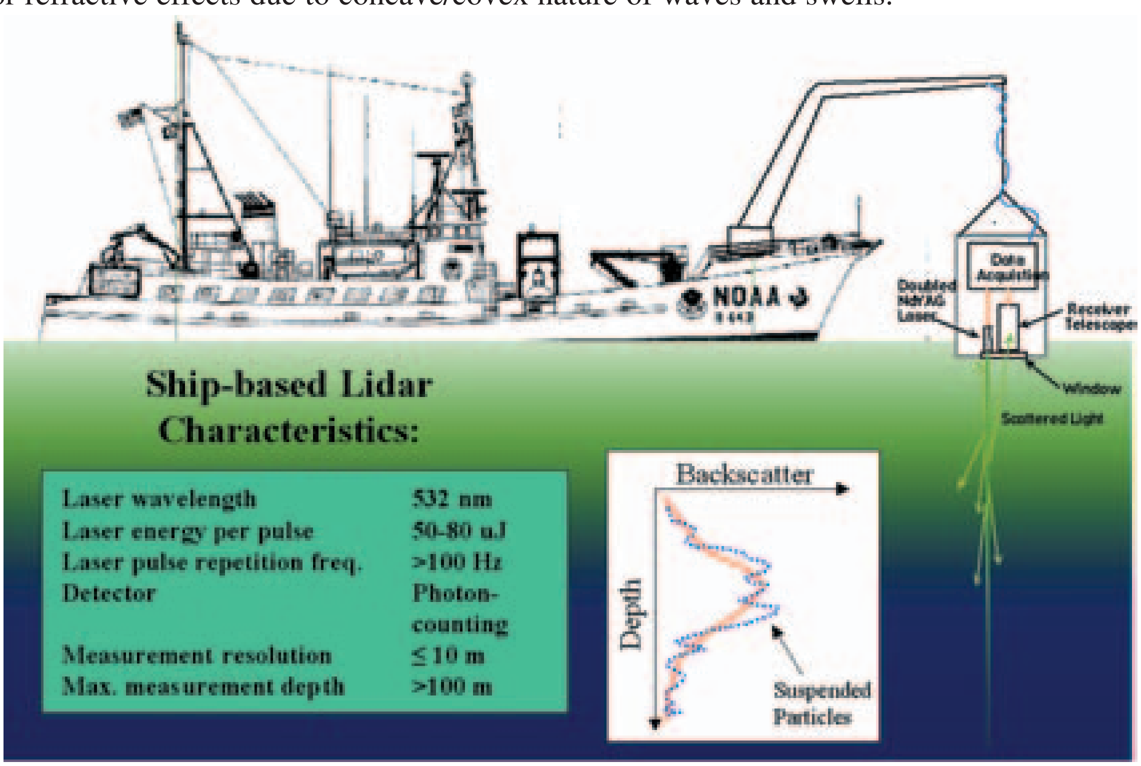

Figure 41. Mixed Layer Lidar Ship-based measurement concept.

Project Scientists: Jonathan A.R. Rall/924, and Michael Behrenfeld/971.1

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Laser Sounder Technique for Remotely Measuring Atmospheric CO_2 Concentrations

Background

This work is developing a new lidar-based approach for the remote measurement of the tropospheric CO_2 concentrations. The main objective of this effort is to demonstrate a technique and technology that will permit measurements of the CO_2 column abundance in the lower troposphere from aircraft at the few ppm level, with a capability of scaling to permit global CO_2 measurements from orbit, the measurement concept is shown in Figure 42.

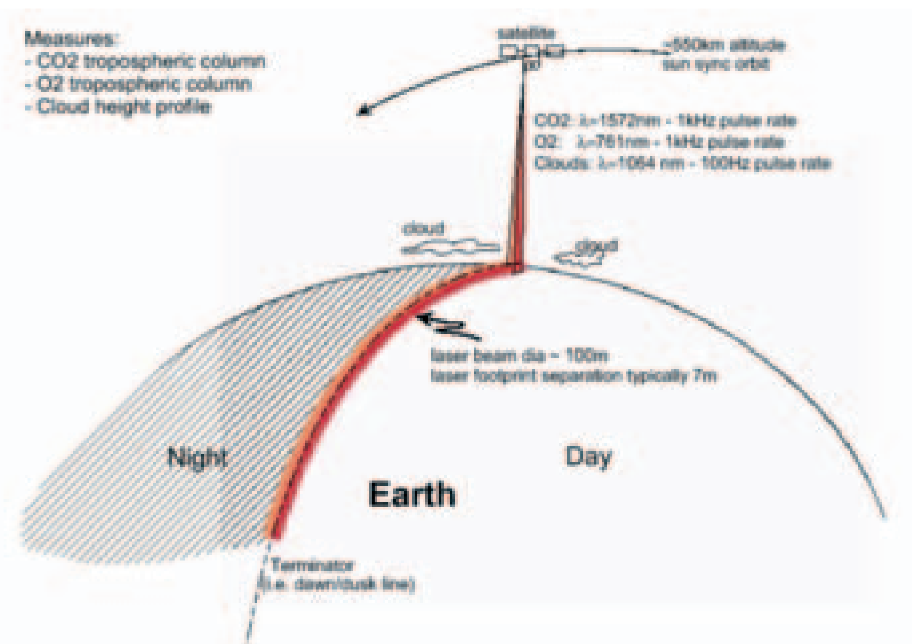

Figure 42. Laser sounder concept and measurement approach. CO_2 is measured in the 1570nm band, O_2 is measured in the 760nm band, and the height profiles of any clouds present in the atmospheric path are measured at 1064nm.

Some important aspects of the variability in atmospheric CO_2 are illustrated by Figures 43 and 44. Figure 43 shows CO_2 profiles obtained by an airborne in situ CO_2 analyzer over Wyoming and Idaho, and over Maine in August of 2000. Note that most of the variability occurs in the lowest few kilometers. Over Maine, photosynthetic uptake of CO_2 is clearly visible as a depletion near the surface, while in the West, uptake has been shut down following a hot, dry summer. The difference in the column CO_2 mixing ratio between the Northeastern and Western U.S. integrated from 0 to 4km is > 5 ppm and thus would be easily detectable by an instrument with 1 ppm precision. Figure 44 shows the covariance between the growth of the planetary boundary layer and diurnal variability in CO_2 mixing ratios. Over the course of the day, the net effects of photosynthesis and respiration are distributed over an atmospheric column of varying height, complicating the interpretation of surface data.

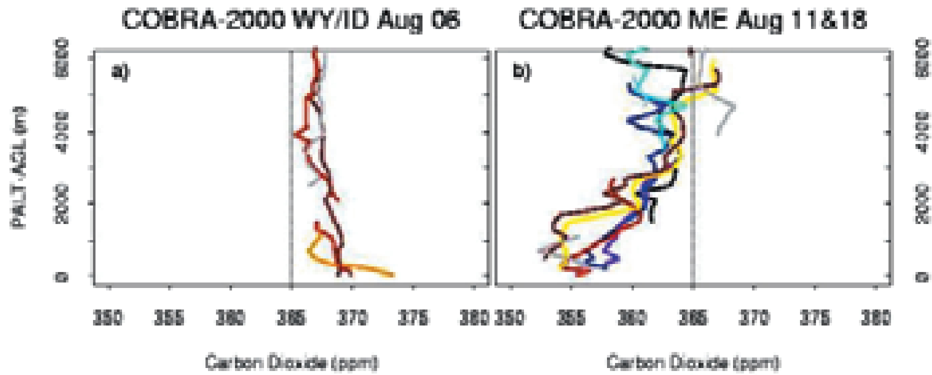

Figure 43. In-situ CO_2 profiles measured over (a) Wyoming and Idaho and (b) Maine collected during the summer of 2000 from a Cessna Citation II aircraft [S. Wofsy, unpublished data].

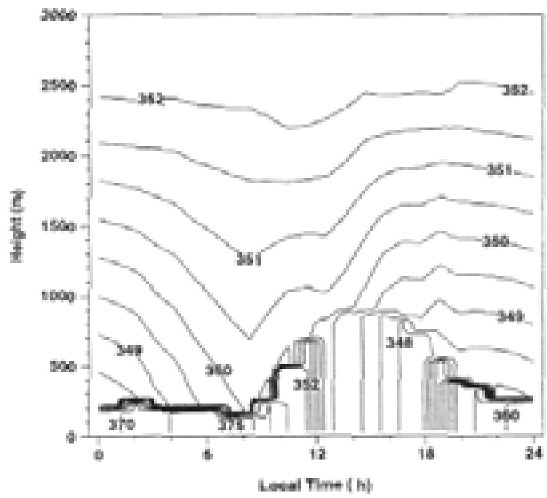

Figure 44. Simulated CO_2 mixing ratios vs. height and time of day over Manaus, Brazil in July [Denning, 1999] illustrating need for dawn-dusk sampling.

Laser Sounder technique

A new laser sounder technique is being developed to provide tropospheric column average CO_2 abundance measurements from space. It measures in a nadir viewing path and weights its measurements to the lowest 4km of the troposphere, where CO_2 variations imposed by surface sources and sinks are largest. Collocated measurements of O_2 column abundance will enable an account for variations in CO_2 caused by topography, surface pressure changes, variable humidity. The 1064nm channel is used to detect the presence of clouds and aerosols.

The laser sounder technique is active and can furnish measurements at dawn and dusk times and will therefore be relatively insensitive to biases caused by large diurnal variations in surface CO_2 mixing ratios. In addition, spatially resolved measurements of the amplitude of the diurnal cycle will provide new information about biogeochemical processes controlling the surface fluxes. For monthly mean global maps with a spatial resolution of approximately 5 x 10^4 km^2, expected precision is 1-2 ppm. Recent studies have estimated that from a space platform precision of better than 1% (3-4 ppm) is needed to reduce uncertainty in the carbon budget beyond what is possible using only data from the existing surface CO_2 monitoring network.

The sounder approach uses three different laser transmitters to permit simultaneous measurement of CO_2 and O_2 extinction, and aerosol backscatter at 1064nm in the same atmospheric path. It directs the co-aligned laser beams from the lidar toward nadir, and measures the energy of the laser backscatter from land and water surfaces. During each measurement period, the two narrow linewidth lasers are rapidly tuned on and off the selected CO_2 and O_2 absorption lines. The receiver records and averages the energies of the laser echoes. The column extinction and column densities of both CO_2 and O_2 are estimated via the differential absorption lidar technique. For the on-line wavelength, the side of the gas absorption line is used, which weights its measurements to 0-4 km in the troposphere. Simultaneous measurements of O_2 column abundance are made using an identical approach using an O_2 line near 770 nm. Atmospheric backscatter profiles are measured simultaneously with the 1064 nm channel, which permits identifying and excluding measurements containing clouds.

This laser sounding technique has several unique advantages. Its lasers have narrow linewidths and very high (MHz-level) spectral stability. It uses sensitive photon counting detection. It can measure at night and in dim-light, it has a narrow measurement swath, and it can simultaneously detect and exclude measurements with clouds or aerosols in the measurement path. For orbital measurements from space, the concept is a lidar measuring at nadir in sun-synchronous orbit. Dawn and dusk measurements will make it possible to sample the diurnal variations in CO_2 mixing ratios in the lower troposphere. A 1-m telescope will be used as the receiver for all wavelengths.

The laser sounder team has demonstrated some key elements of the laser, detector and receiver in the laboratory. These include stable measurements of CO_2 line shapes in an absorption cell using a fiber amplifier seeded by a tunable diode laser as shown in Figure 45. The plan for the next year is to complete the laboratory work and demonstrate the performance of the CO_2 channel over a horizontal or vertical path. The team has examined the feasibility of a ground based instrument and an airborne instrument operating at a 5km altitude. The use of commercially available fiber lasers and a 10-20 cm receiver lens appears to be sufficient for useful measurements with 5 second integration times. This work is supported by the ESTO ATIP program.

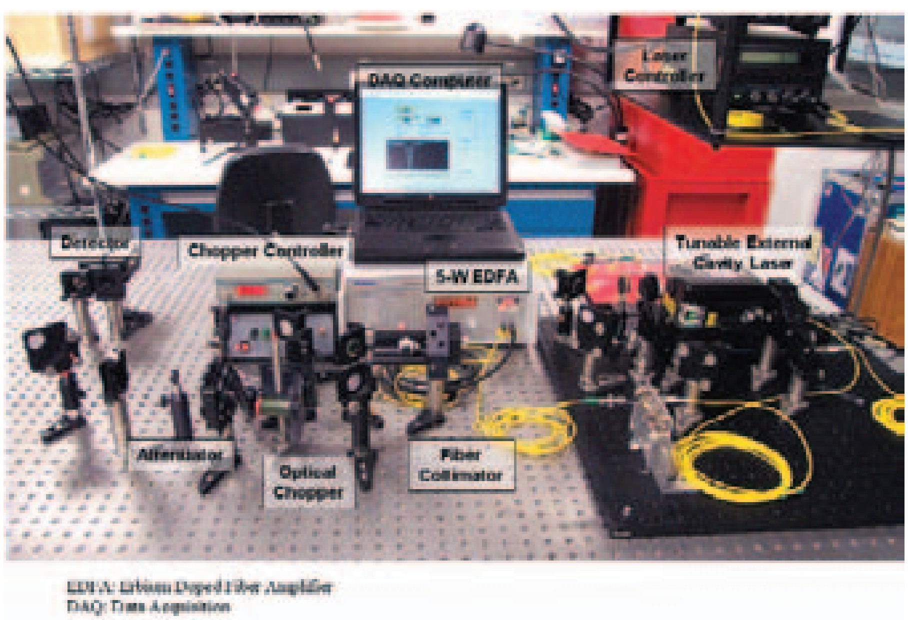

Figure 45. Laser Transmitter breadboard for CO_2 sounder

Project Scientists: James B. Abshire, G. Collatz, X. Sun, A. E. Andrews, and H. Riris

References:

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Miniature Lidar at Remote Sites in Antarctica

Background

We are developing a new small, low-power lidar, which can operate autonomously when deployed at remote unattended sites. The plan is to incrementally add these lidar to selected sites on the Greenland ice sheet and co-locating them with remote Automatic Weather Station (AWS) sites in Antarctica. The NSF Office of Polar Programs provides support to place the weather stations in remote areas of Antarctica in support of meteorological research and operations. Measurements from the network of atmospheric lidar will provide knowledge regarding the temporal evolution and spatial extent of polar stratospheric clouds (PSC). These clouds play a crucial role in the destruction of stratospheric ozone over Antarctica. In addition, the lidar will monitor and record the general atmospheric conditions (transmission and backscatter) of the overlying atmosphere, which will benefit the GLAS measurements on the ICESat mission.

In 1998 a prototype lidar was developed for use in the NSF's unattended Automated Geophysical Observatories (AGOs) in Antarctica. The AGO lidar design was ruggedized to be compatible with the severe constraints and temperature environment of the remote AGO platforms. The lidar was designed to monitor the polar atmosphere to 30km altitude. It collected and reported measurements of atmospheric backscatter profiles at 666nm using two cross-polarized receiver channels. The lidar operated completely autonomously and its design is a prototype for future versions.

The lidar transmitter used two GSFC-designed diode lasers with two photon counting detectors in its receiver. The laser transmitters were very power efficient and used a single semiconductor optical amplifier in an external optical cavity. This laser transmitter operated at 666nm and produced 1µsec wide laser pulses with energies of 0.5µJ at a 4 kHz pulse rate. The power drawn by the entire lidar was only 8 Watts. An ARGOS transmitter was incorporated into the lidar electronics and the lidar reported its measurements back to Goddard via the ARGOS receivers on NOAA satellites. All other instruments on the AGO platforms logged their data onto a common disk inside the enclosures, which are read only once per year.

Deployment and Operation

The prototype lidar was installed in AGO Platform P1 during January 1999. The lidar successfully operated continuously from January through July 1999, when the AGO P1 platform's power supply failed. When this occurred, the interior temperature of the enclosure slowly cooled to –80°C. Unfortunately, the lidar's atmospheric measurements at the site were compromised by icing of the optical window used in the AGO enclosure. Icing was caused by the installation crew, and should not be a problem at the AWS sites. Otherwise, while the P1 site had power, the lidar operated very successfully.

The prototype AGO lidar was removed from the P1 site last spring and was returned to GSFC. Examination showed that one of the two laser transmitters had failed in transit back and one detector failed during its deployment on the polar plateau. However, once reassembled with a replacement detector, AGO Lidar powered up successfully in early November and once again began taking data autonomously at GSFC. The plots in Figure 46show sample AGO Lidar measurements acquired on 11/27/01. The lidar was turned on just after sunset and operated until well after sunrise the next morning. Data was integrated in 10 minute slices and has had background subtraction and range correction performed. No smoothing or averaging has been applied. Channel 1 is the parallel receiver channel and Channel 2 is the cross-polarized channel.

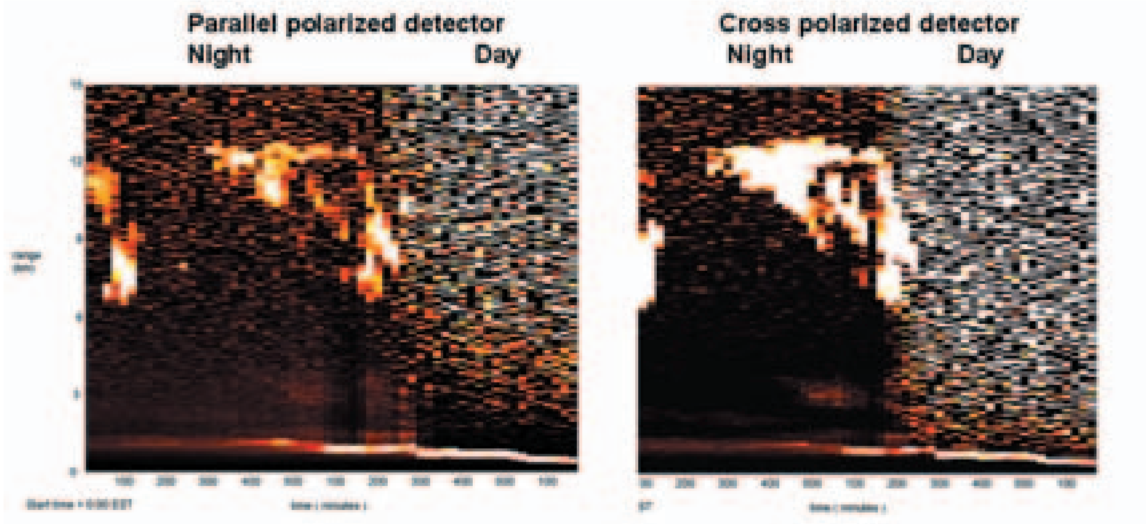

Figure 46.

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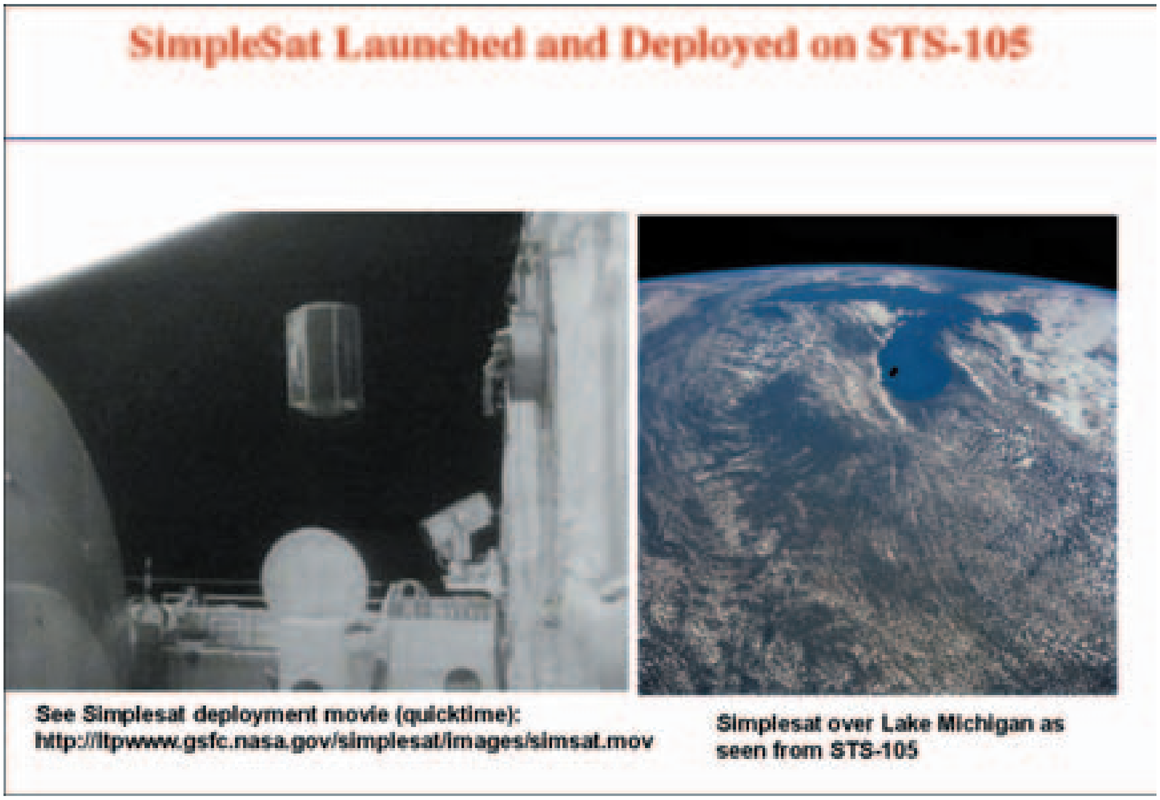
Simplesat Optical Microsatellite Experiment

The Simplesat microsatellite experiment is an effort to design, construct, and fly a capable but inexpensive 3-axis stabilized spacecraft with precision optical pointing capability. It is carried into space by the Space Shuttle as part of the Hitchhiker payload program. Simplesat becomes a free flying satellite after it is ejected into space by springs from its canister. The Simplesat-1 satellite contained a GPS receiver capable of determining its orientation and a telescope and CCD sensor for fine attitude determination and control and communications to ground via ham radio equipment. All other Simplesat parts are commercial or industrial grade. The objective is for the satellite's orientation information to be used to try to control the pointing direction of the satellite to the arc-second level. Stars are used as calibration targets. The eventual goal for the Simplesat effort is to develop a microsatellite with precision pointing capability, with an operating lifetime of a about month, which can be built at a cost compatible with a typical several year research grant.

The initial flight experiment was made with Simplesat-1, whose spacecraft was launched on August 10, 2001 from the Orbiter Discovery on Mission STS-105. After visiting the Space Station the Shuttle crew used a spring ejection system to deploy Simplesat from its Hitchhiker canister. The deployment was nominal with the satellite appearing to be in good mechanical shape prior to the spring ejection from the Hitchhiker canister.



The Simplesat ground station has a steerable helical antenna mounted atop NASA GSFC's building 33. Daily contact attempts with the spacecraft were made since it was deployed. Despite numerous attempts and ground station improvements, no satellite signals were detected from Simplesat-1. During the mission many possible causes for lack of detected signal were analyzed. One likely candidate cause is possible electrical arcing within Simplesat's radio transmitter module.

On January 30, 2002 Simplesat-1 reentered the Earth's atmosphere northeast of Australia at latitude 20 degrees North and longitude 157 degrees East. It completed 5 months and 2500 orbits above the Earth. A GSFC technical peer review has been recently conducted and plans for a Simplesat-2 experiment are being discussed. (see http://ltpwww.gsfc.nasa.gov/simplesat/ for more details).

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2001 Refereed Publications

The Laboratory's publications for the year 2001 are listed in the various discipline sections. The total number of our refereed publications that actually appeared in print in 2001 was 112 (i.e., this does not include papers that were "accepted" and/or "in press"). This figure includes refereed journal articles, book chapters, and/or books authored by our civil servants, post doc's, visiting scientists, contractors, and people from other agencies co-located in our physical space who conduct joint research with us. The 8 publications in Laser Measurements & Technology are listed below.

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Awards

NASA Group Achievement Award for work with the MODIS Characterization Support Team (MCST).